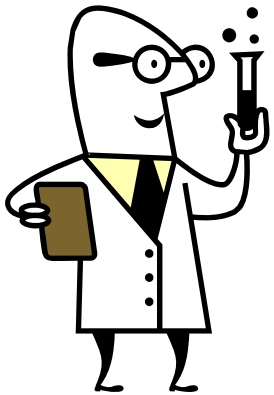
# Accounting for Scientists: Tevatron Luminosity



Vladimir Shiltsev
Fermilab AD/Tevatron

# Content:

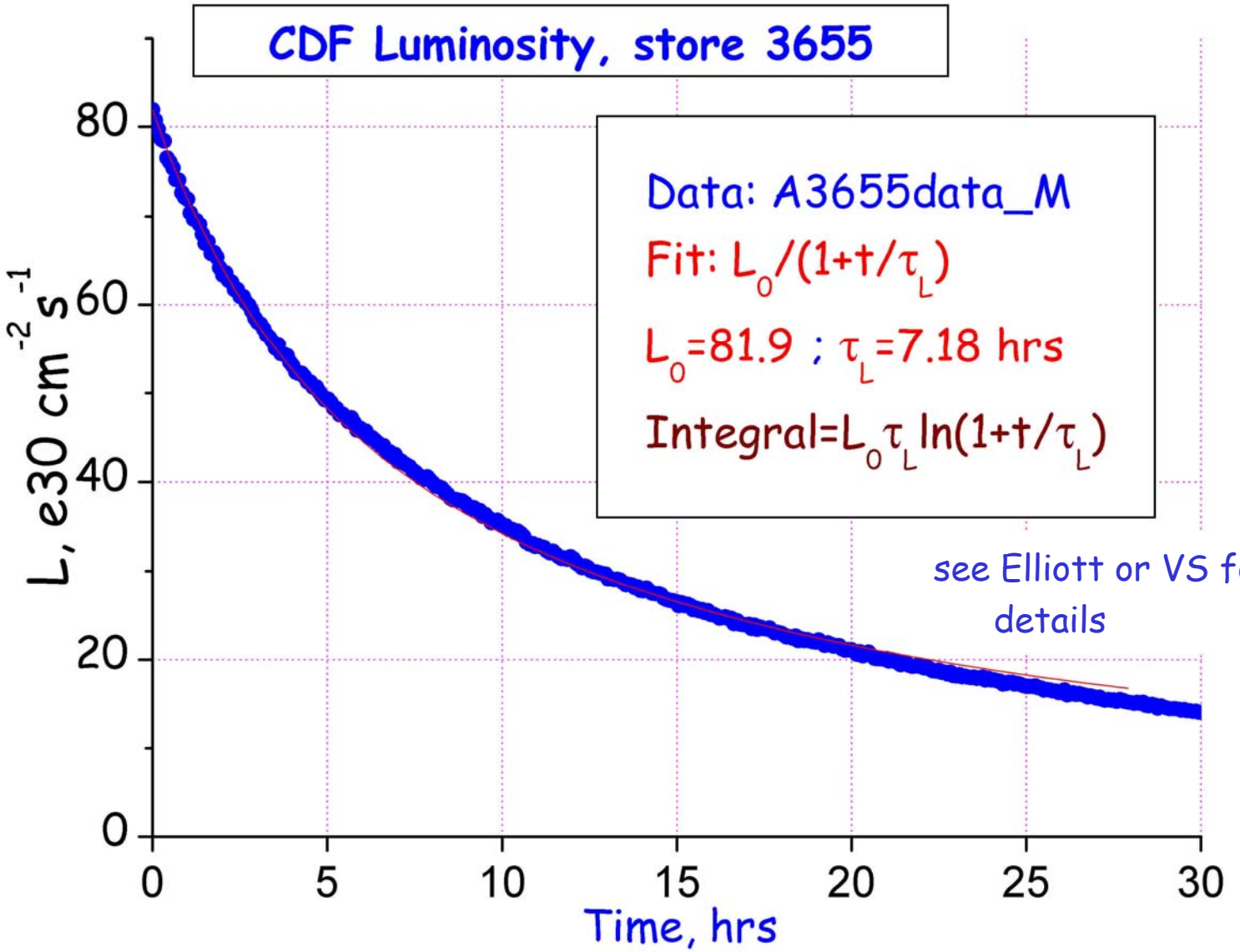
- Introduction: (ir)relevant comments
- Luminosity progress:
  - 2002-2003
  - Shutdown'03 - Mar'04
  - Mar'04 – July '04
  - Shutdown'04 – May'05
- Open Questions and Conclusions

# Introductory Notes: Lumi and Integral

$$L = \frac{3\gamma \ f_0 \ B \ N_{\bar{p}} N_p}{\pi\beta^* \left(\varepsilon_p + \varepsilon_{\bar{p}}\right)} H\left(\sigma_l / \beta^*\right)$$

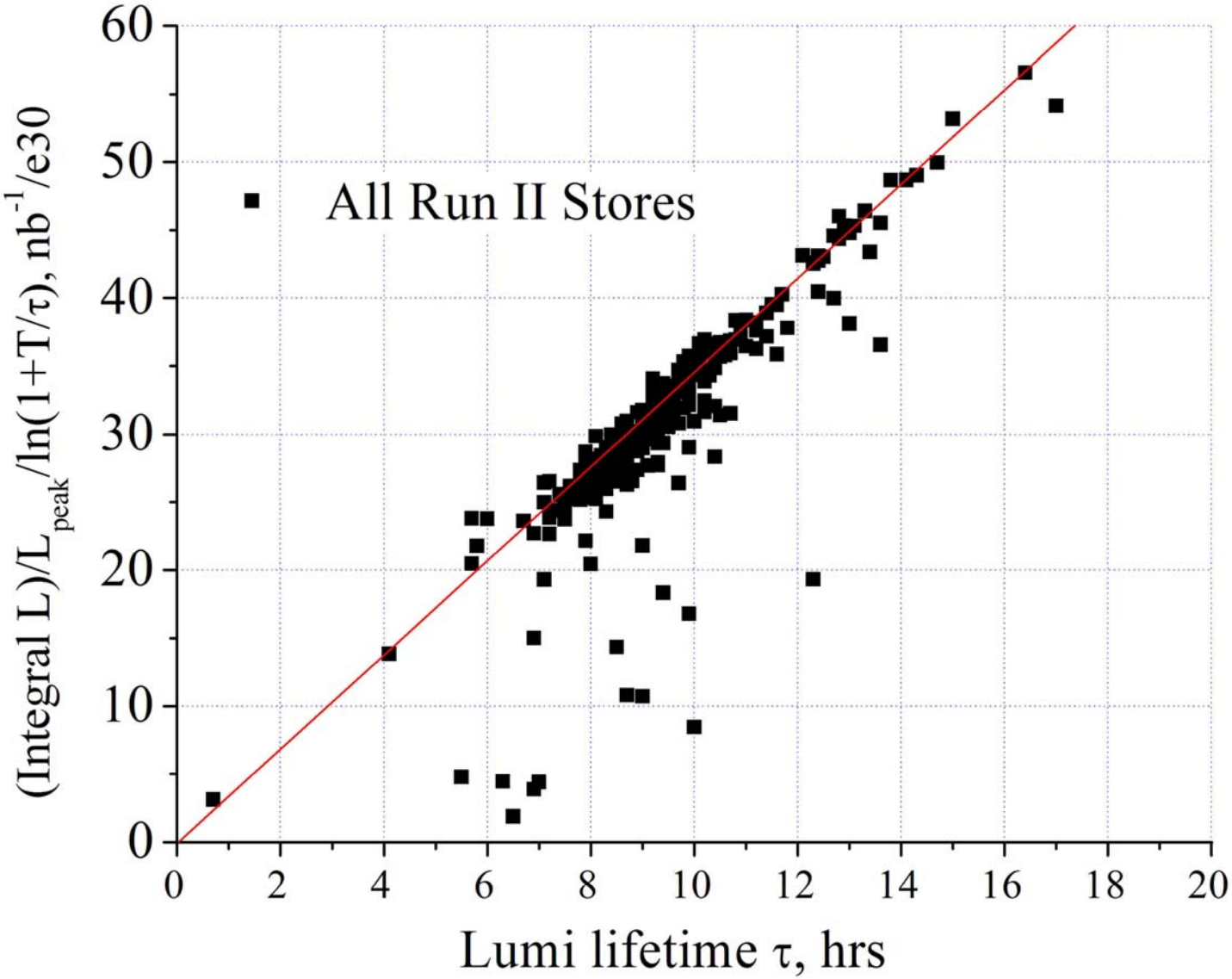
- Peak Luminosity: primary factors
  - Beta* at IP and bunchlength: H(x)/beta^*
  - Emittances
  - Number of protons: $N_p$
  - Number of antiprotons: $BN_{pbar}$

# Integral: Log in time, $\propto L_0$ and Lifetime

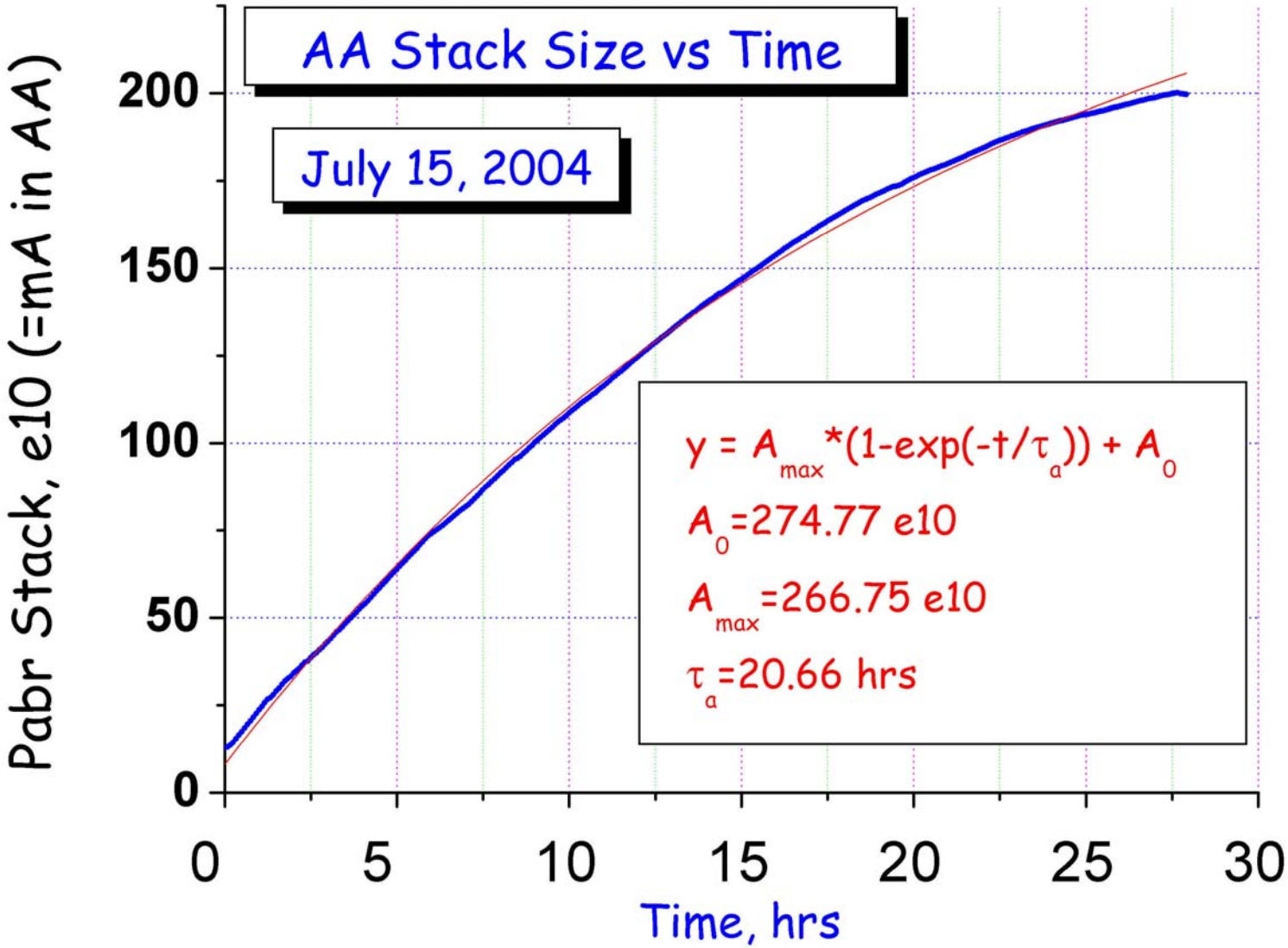



see Elliott or VS for more details

# Integral Is Indeed as Mentioned Above:



# Integral: $N_a$ Exponentially Saturates



# Luminosity Integral

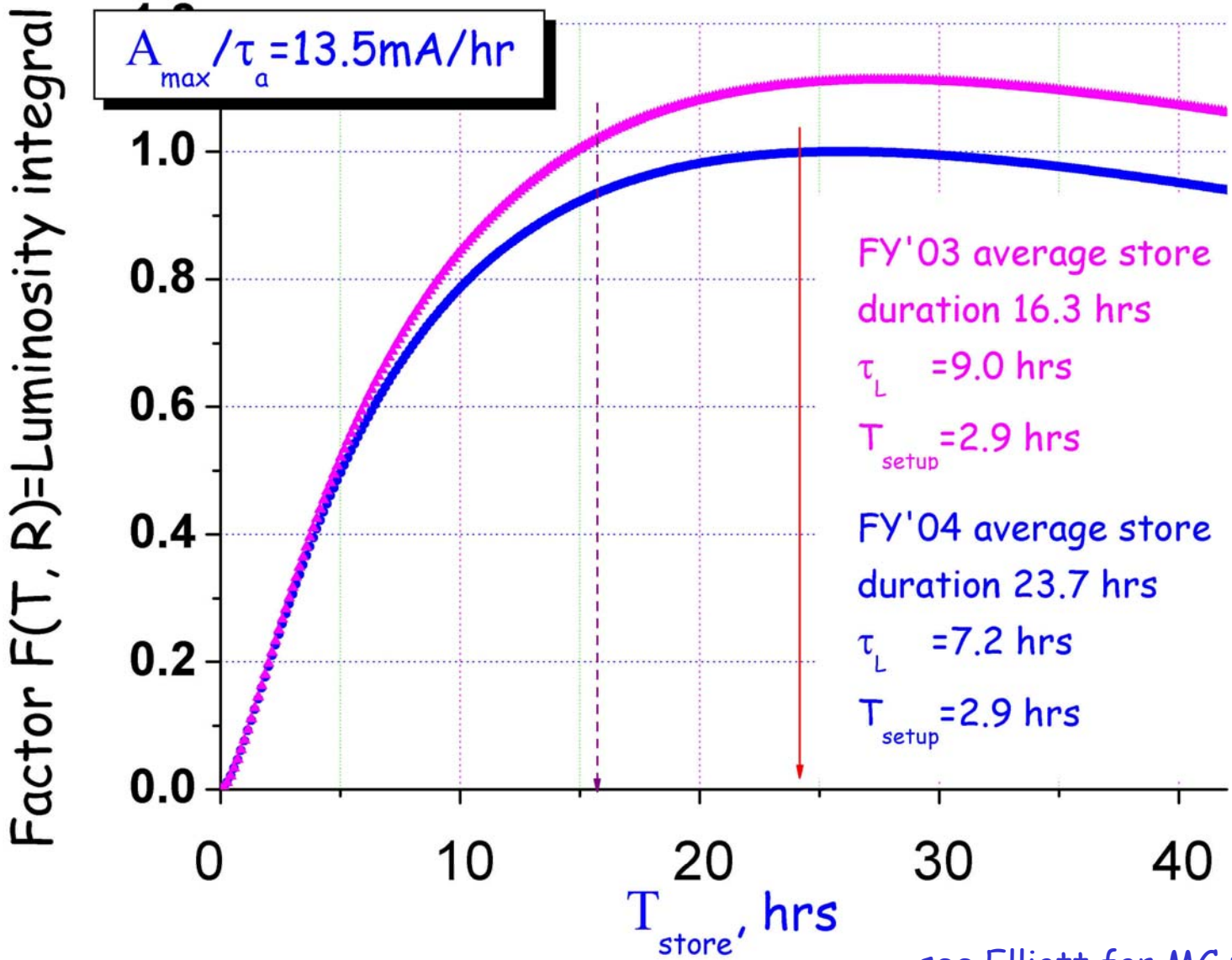
$$I = \int L dt = N_{stores} \tau_L L_0 \ln(1 + T/\tau_L)$$

$$\propto N_{weeks} \eta_{up} \frac{H\left(\frac{\sigma_l}{\beta^*}\right) N_p \eta_a A_{\max}}{\beta^* \left(\varepsilon_p + \varepsilon_{\bar{p}}\right)} F(T, \tau_L, \tau_A, \tau_{SS})$$

$$F = \frac{\tau_L}{T + \tau_{SS}} \ln(1 + T/\tau_L)\left[1 - \exp(-T/\tau_A)\right]$$

see next slide

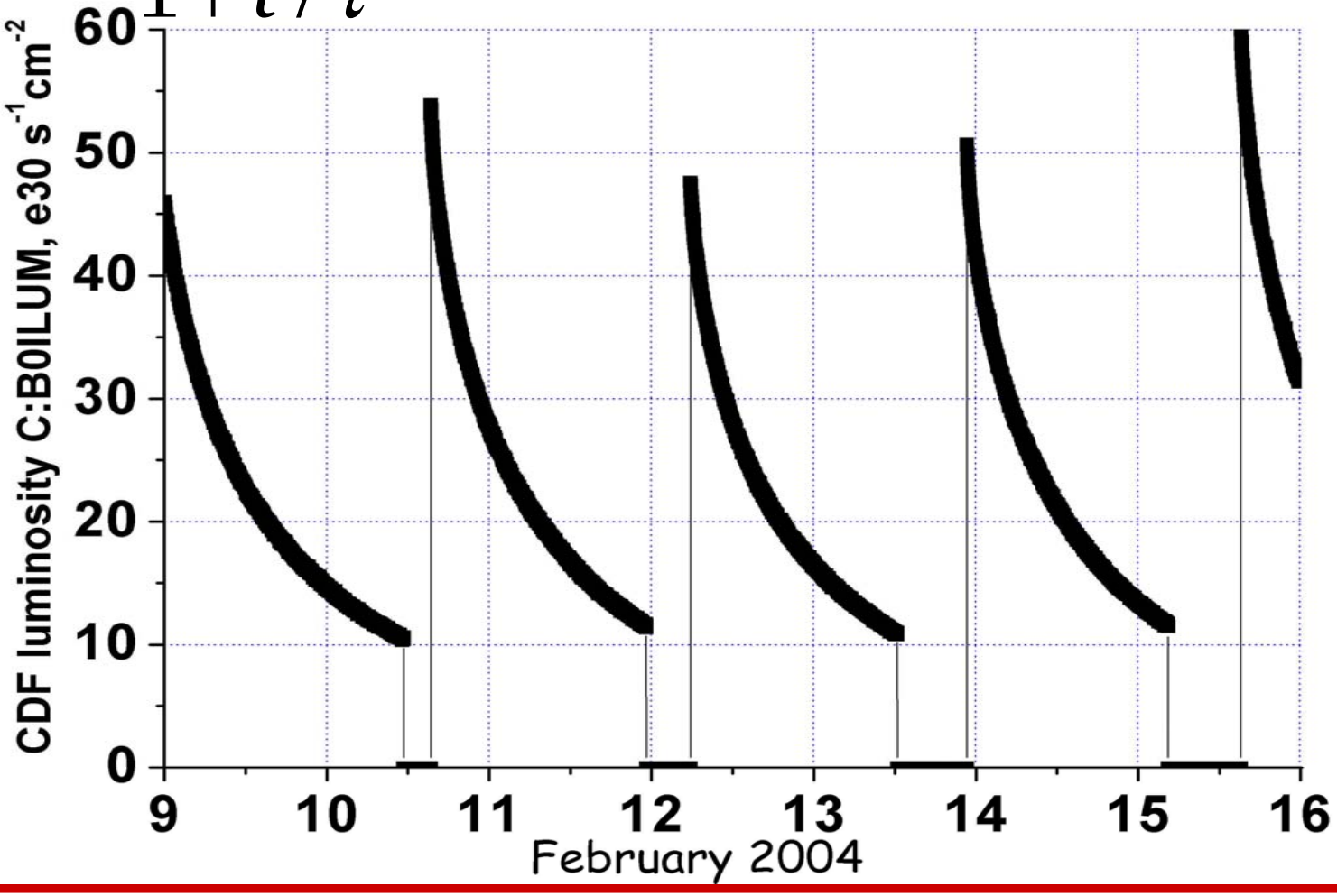
# Store Length Optimization Factor *F*



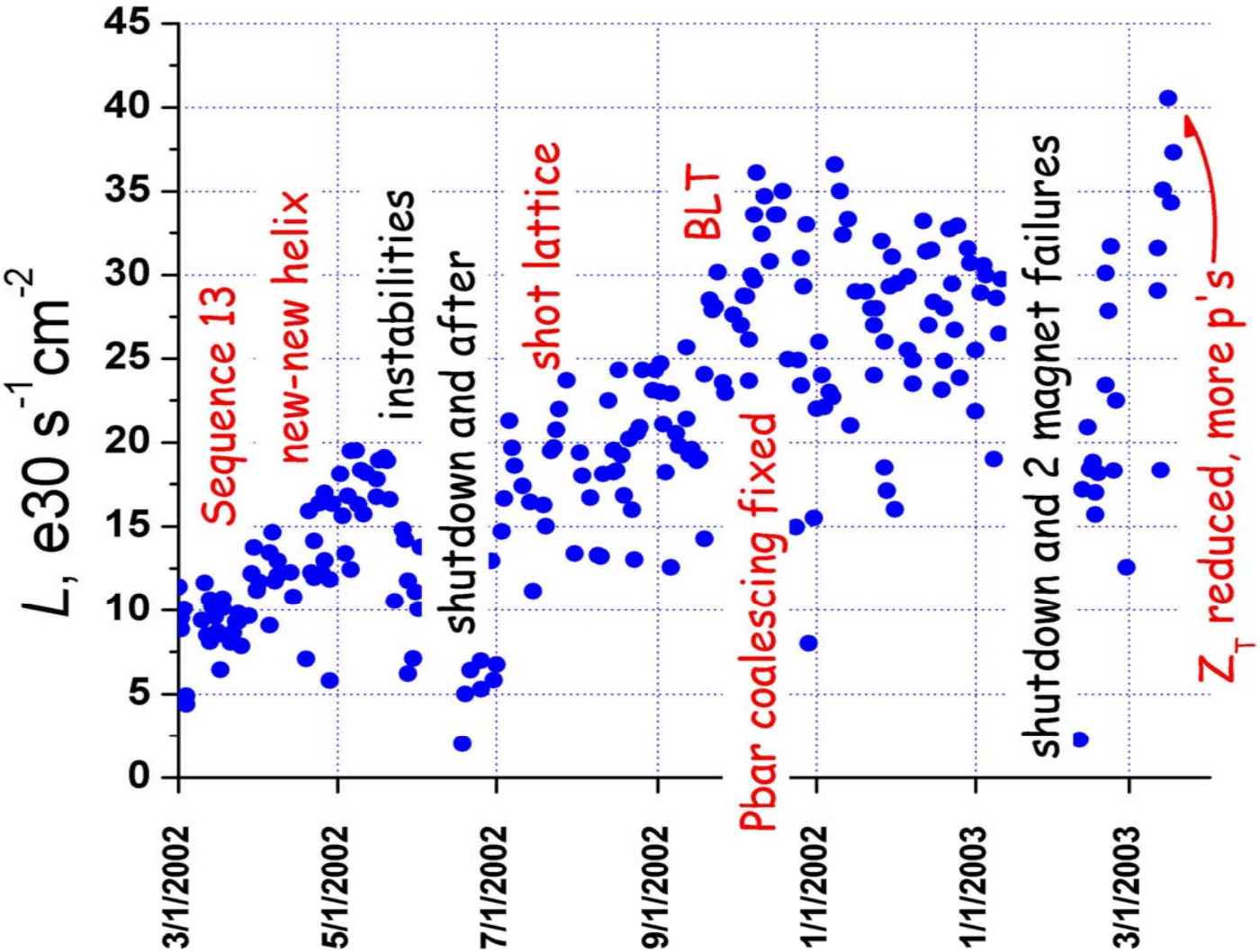

see Elliott for MC model

# Integrated Luminosity Factors

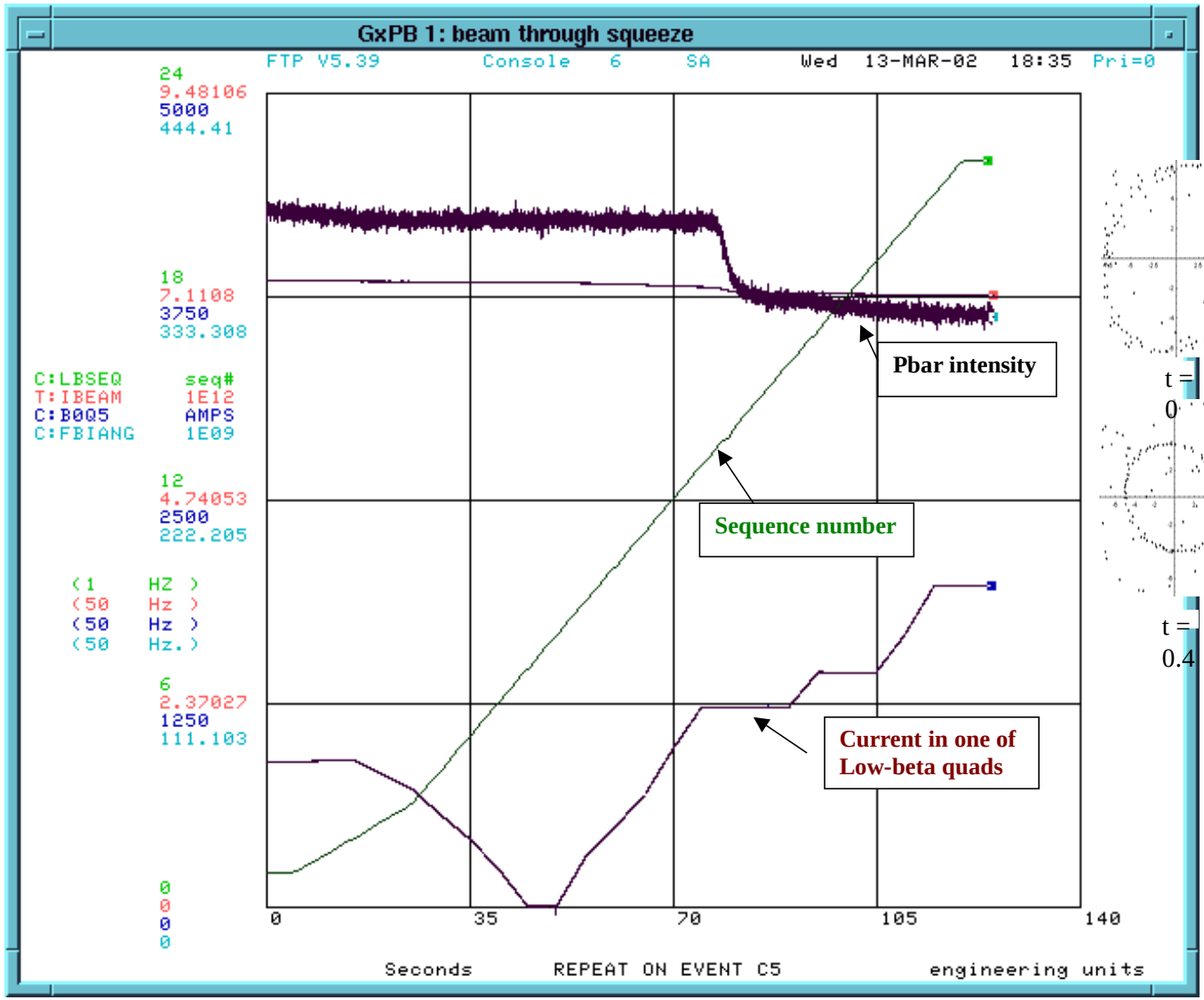
$$I = \int \frac{L_{peak}}{1 + t/\tau} dt \approx L_{peak} \cdot \tau \cdot \ln(1 + T/\tau) \cdot \mathrm{N}_{stores}$$



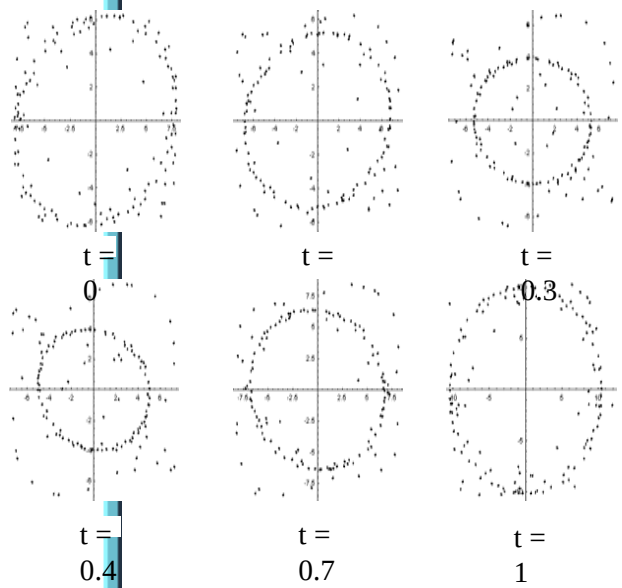
# Tevatron 2002-2003



# "Sequence 13"




Minimum separation turned out to be only **1.8σ**!




**The separation has been increased to 2.7σ and the loss gone**

# Helix Work: Started in 2002.. Still in progress

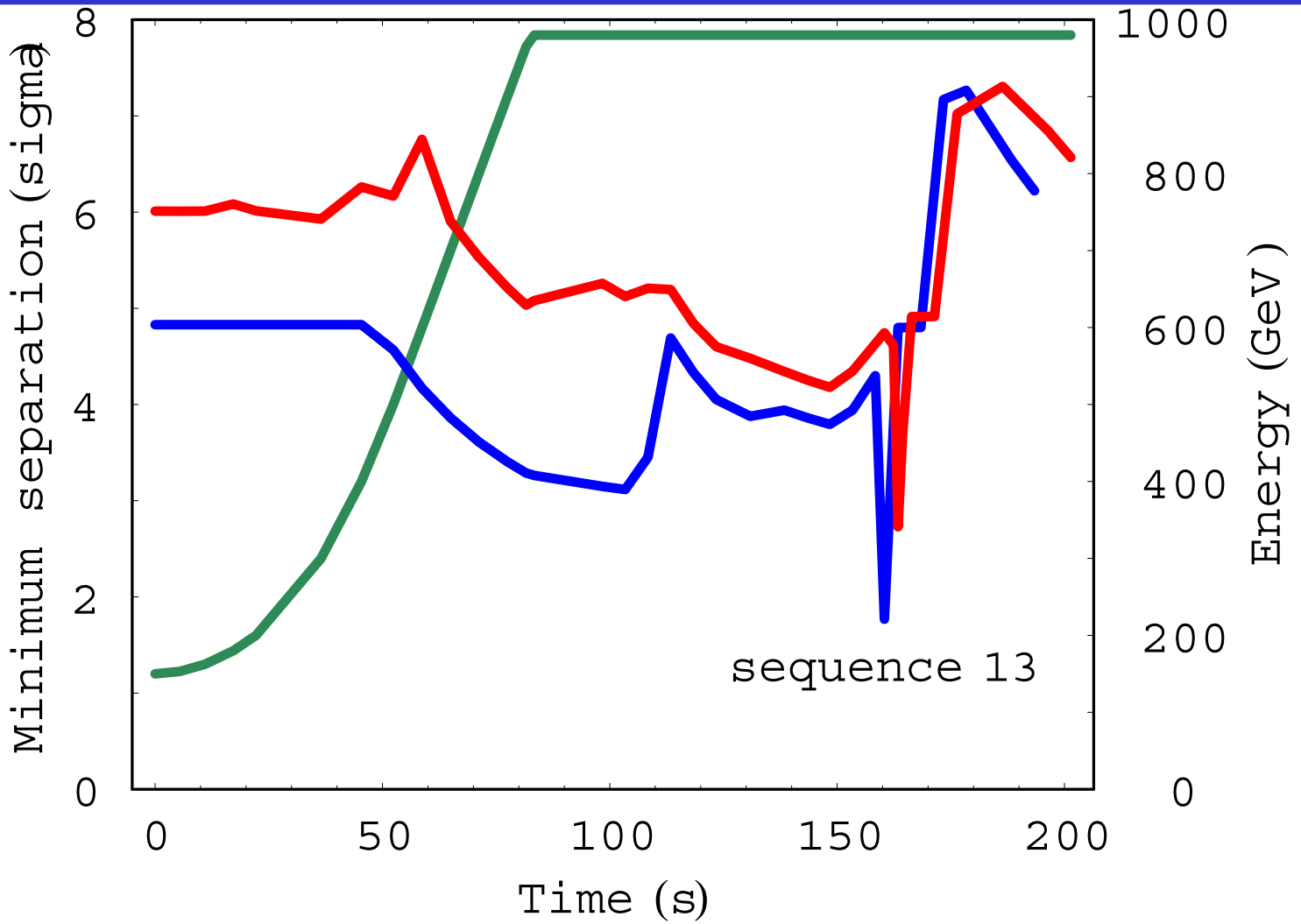
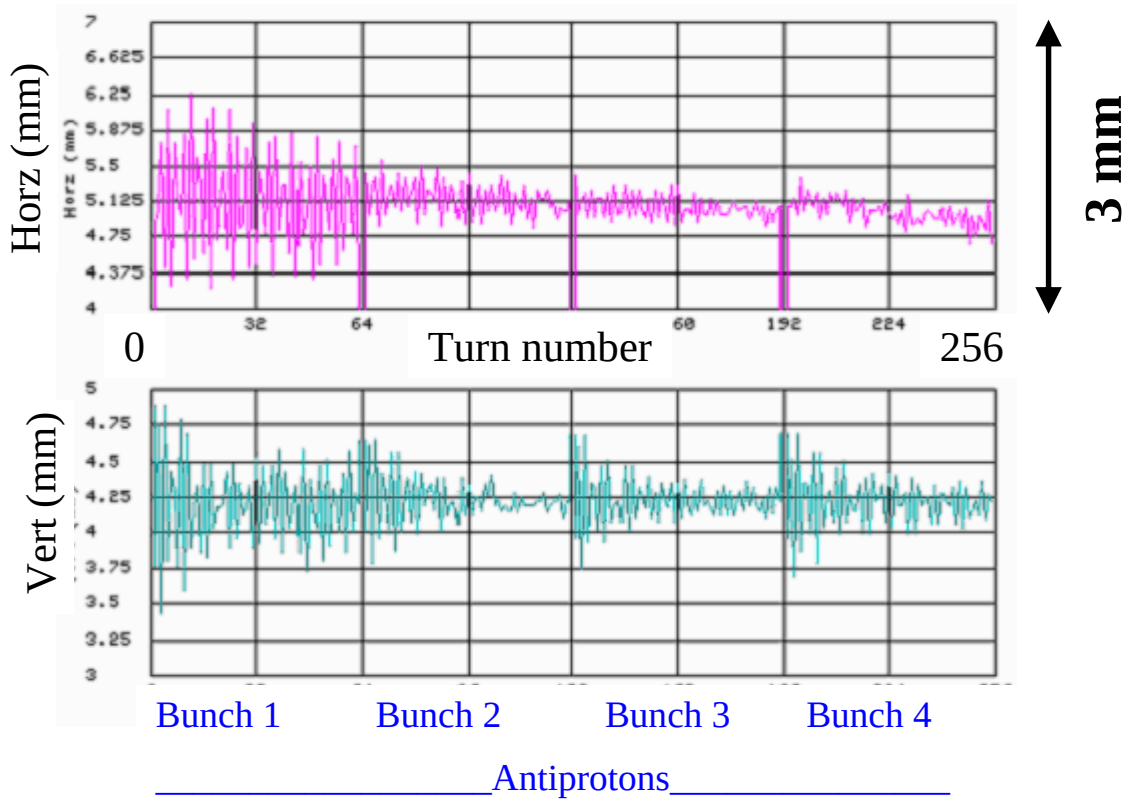


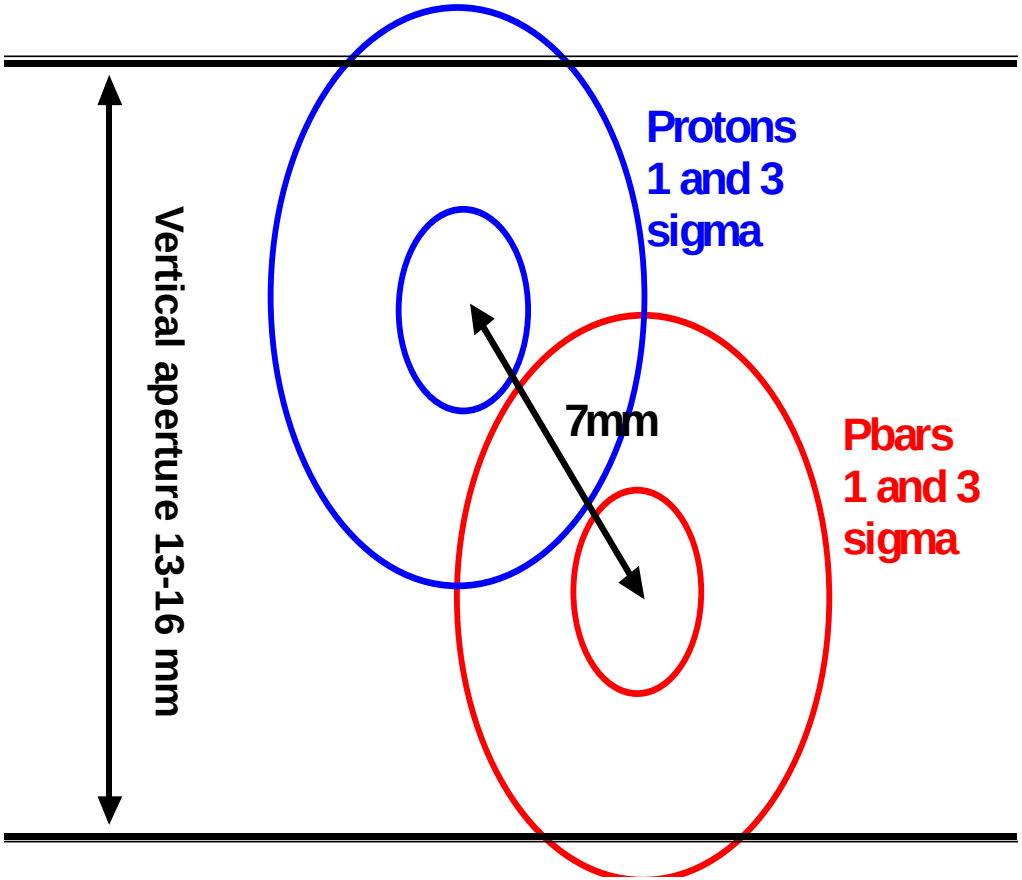

Fig.2.1: Minimum radial separation on ramp and during the low-beta squeeze. Green line – beam energy *E(t)*. Blue and red lines represent *S(t)* circa January 2002 and August 2004, correspondingly.

# Injection Oscillations in Tevatron




- Turn-by-turn position monitor, (and bunch-by-bunch for pbar)
- Use to tune up injection closure
- 1 mm corresponds to roughly 3-4π emittance blowup
- ~3-5π pbar emittance blowup eliminated

# C0 Lambertson Replacement




Proton and pbar beam position and sizes on the helix at the location of C0 Lambertson

Pbar lifetime depends on emittances and helix size.

C0 Lambertson is severest aperture restriction. (See picture)

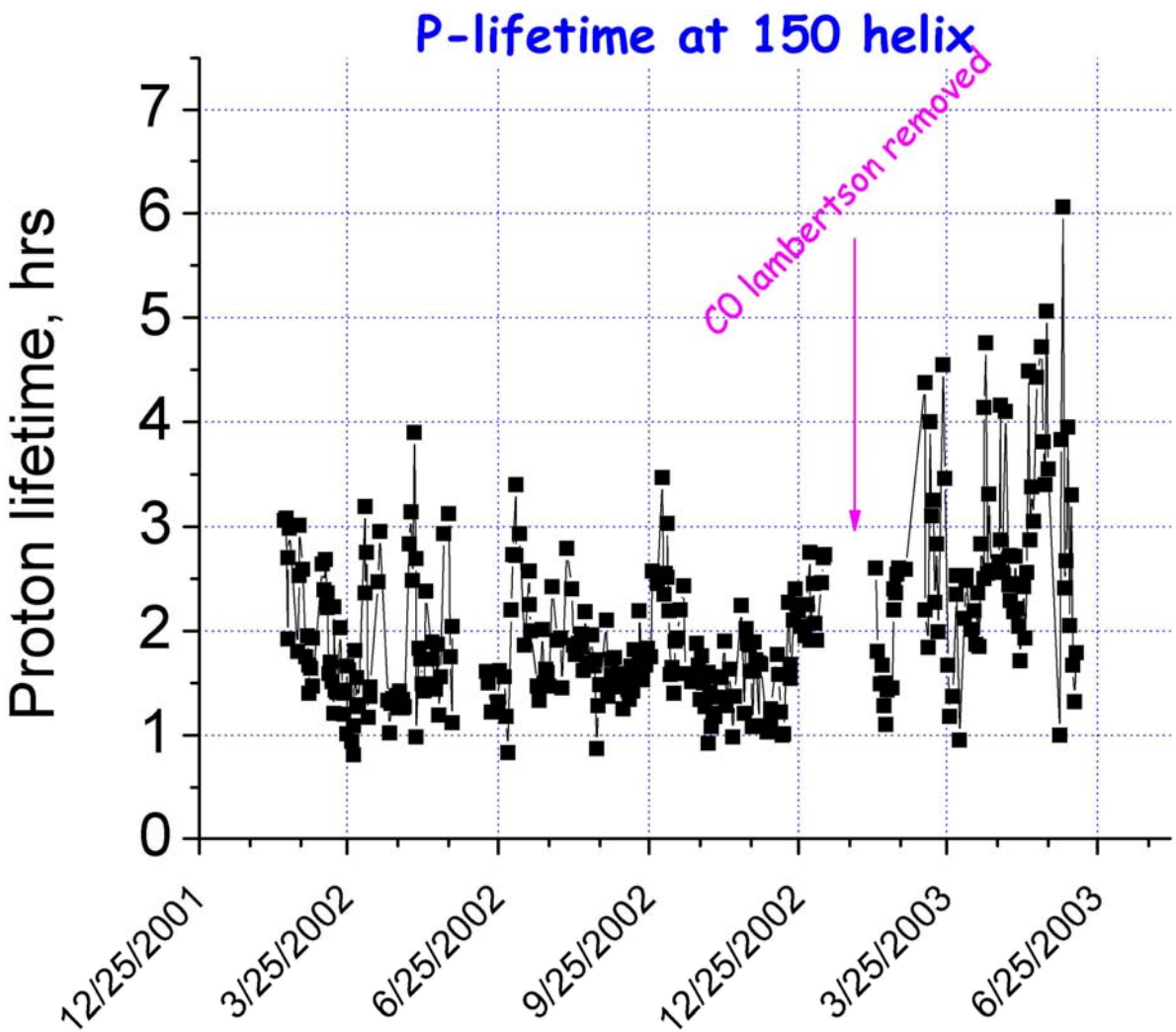
Design injection helix modified and optimized to fit tight C0 aperture ("new-new helix")

(Jan 2003)

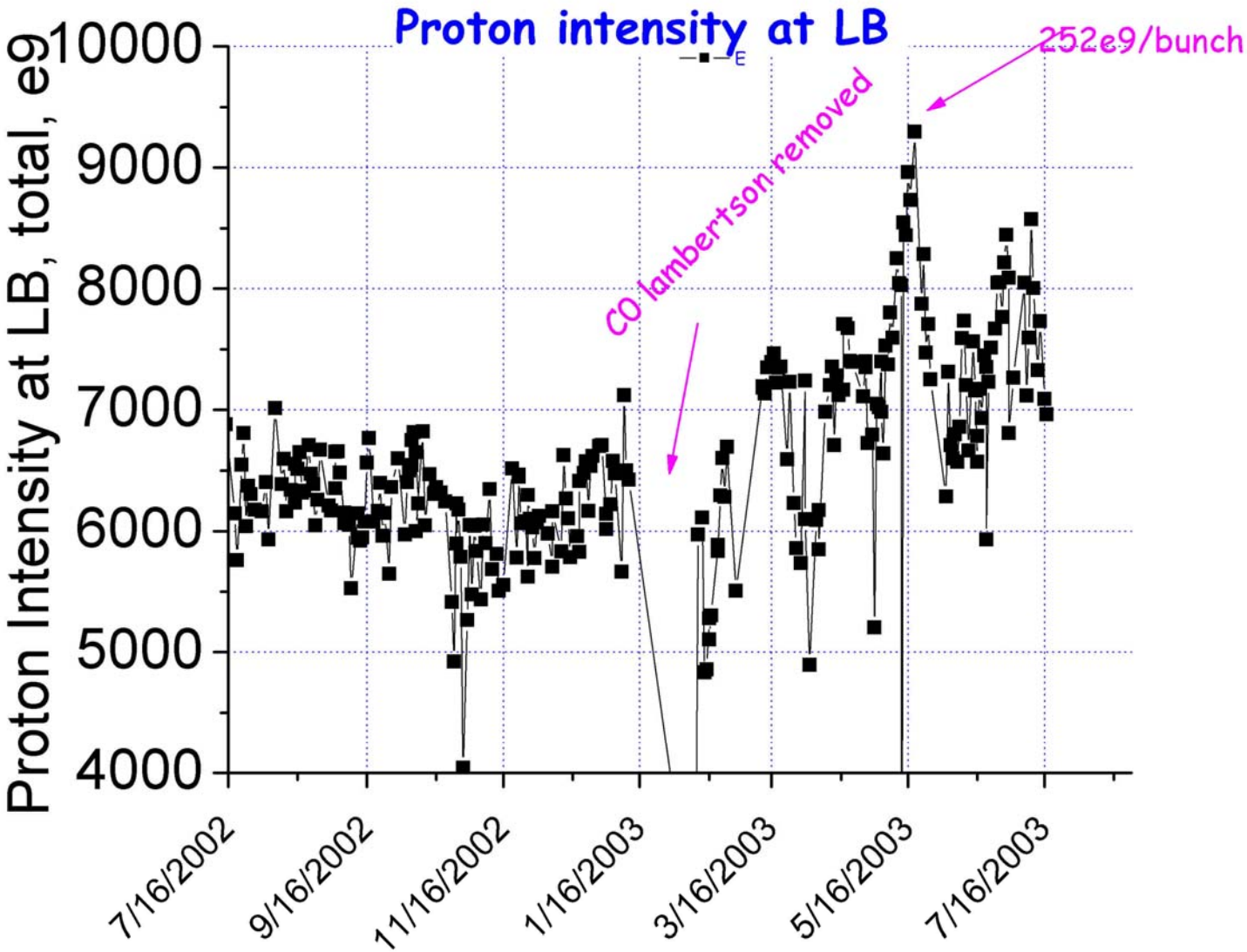
Replace C0 Lambertsons

Gain 25 mm vertically

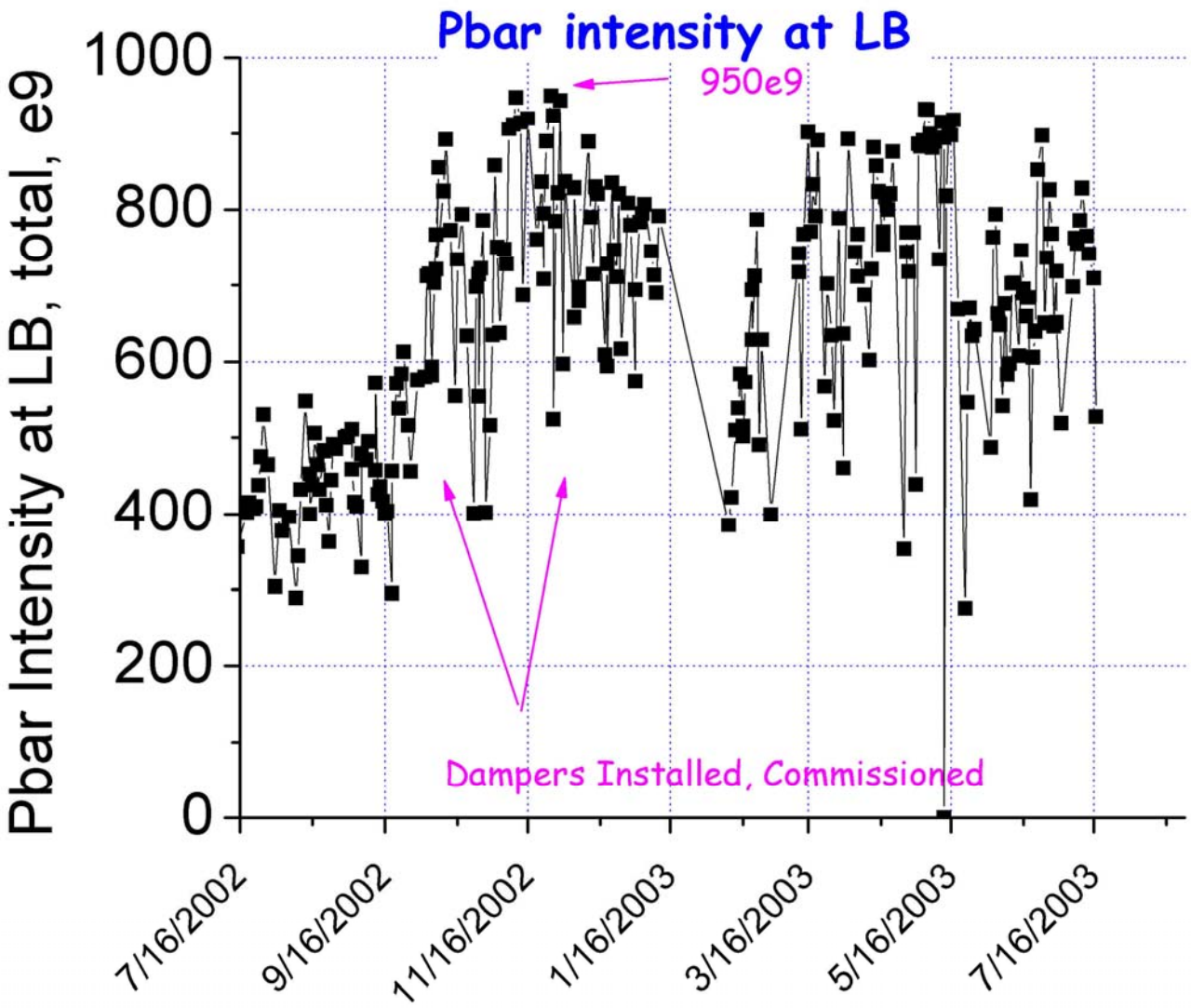
# CO Lamberston Removal (Jan'03) – Lifetime improved



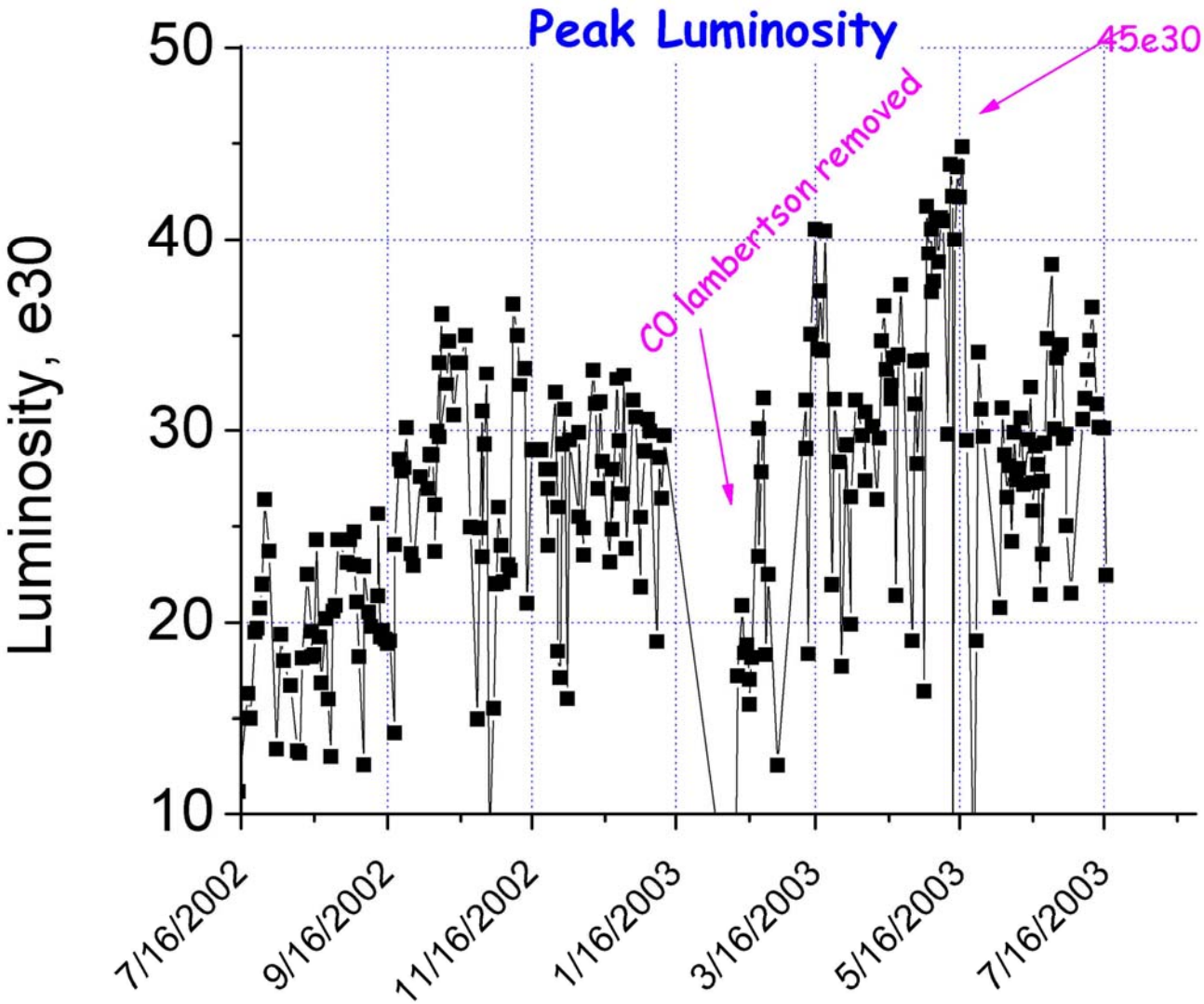
# CO Lambertson removed -> p-Intensity Increased



# CO Lamberston Removal – No effect on Pbars



# Net effect -> Luminosity Increased



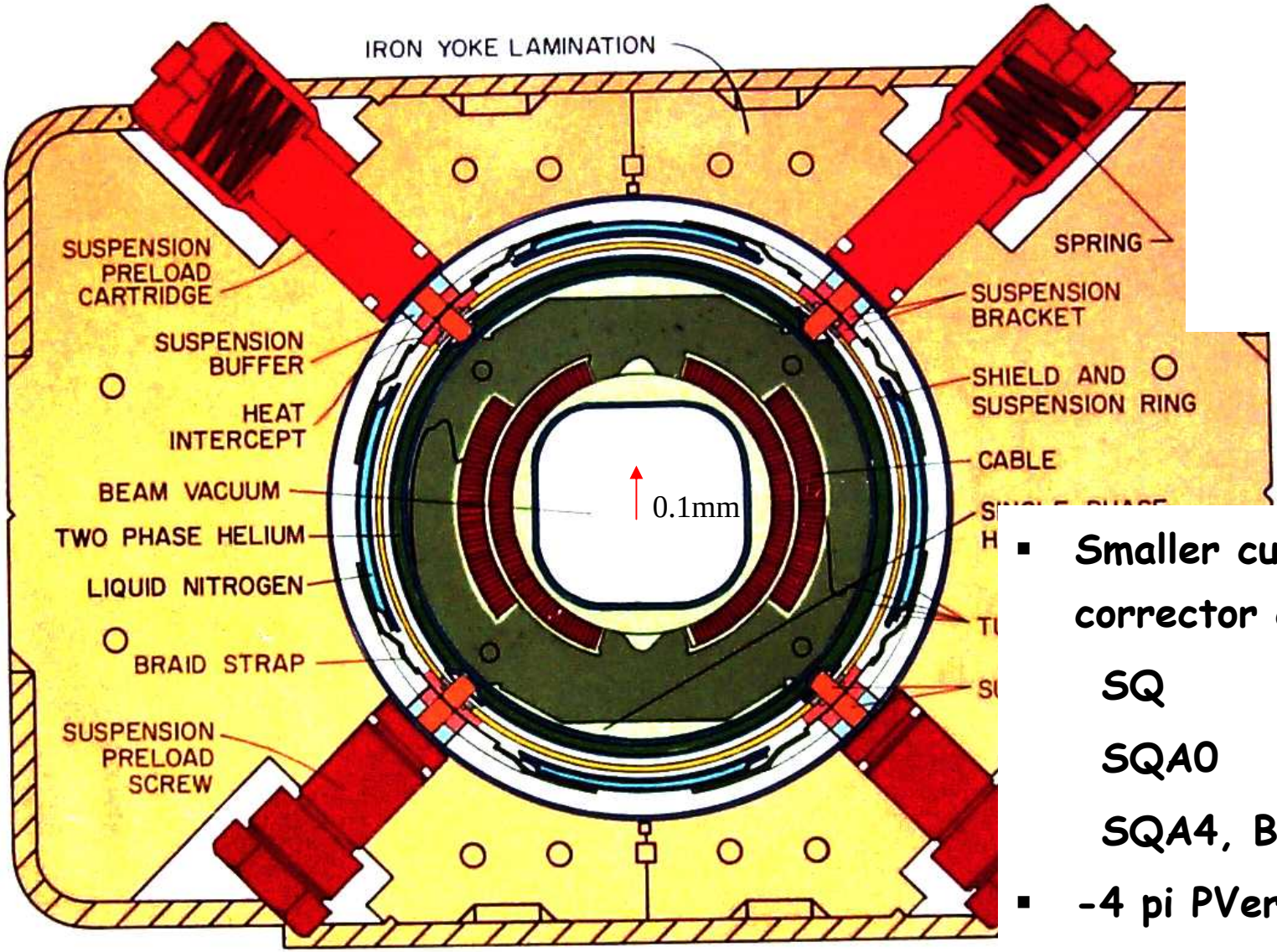
# $\mathcal{L}$-progress '02 – '03

| | | | |
|---|---|---|---|
| "Sequence 13" fixed | Tev | Spring'02 | x 1.40 |
| "New-new" injection helix | Tev | Summer'02 | x 1.15 |
| "Shot lattice" | AA | Summer'02 | x 1.40 |
| Pbar emittance at injection | Tev/Lines | Fall'02 | x 1.20 |
| Pbar coalescing improved | MI | Fall'02 | x 1.15 |
| C0 Lambertson removal | Tev | Feb'03 | x 1.15 |

….plus additional improvements in the Tevatron:

- Tunes/coupling/chromaticities at 150/ramp/LB
- Orbit smoothing
- Longitudinal damper to stop $\sigma_s$ blowup
- Transverse dampers improve 150 Gev lifetime
- Separator scans

# Reshimming Tevatron Dipoles



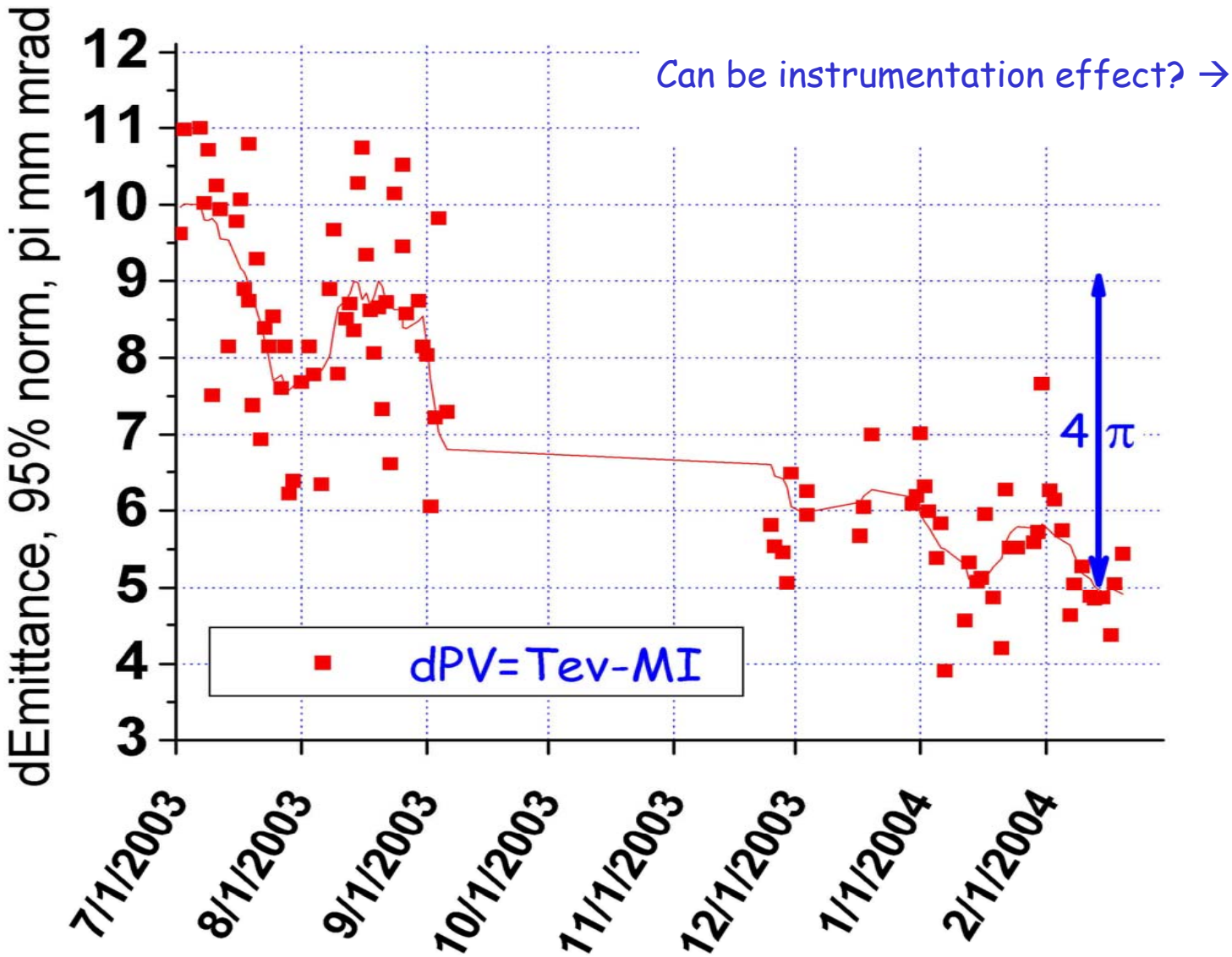

M.Syphers

D.Harding

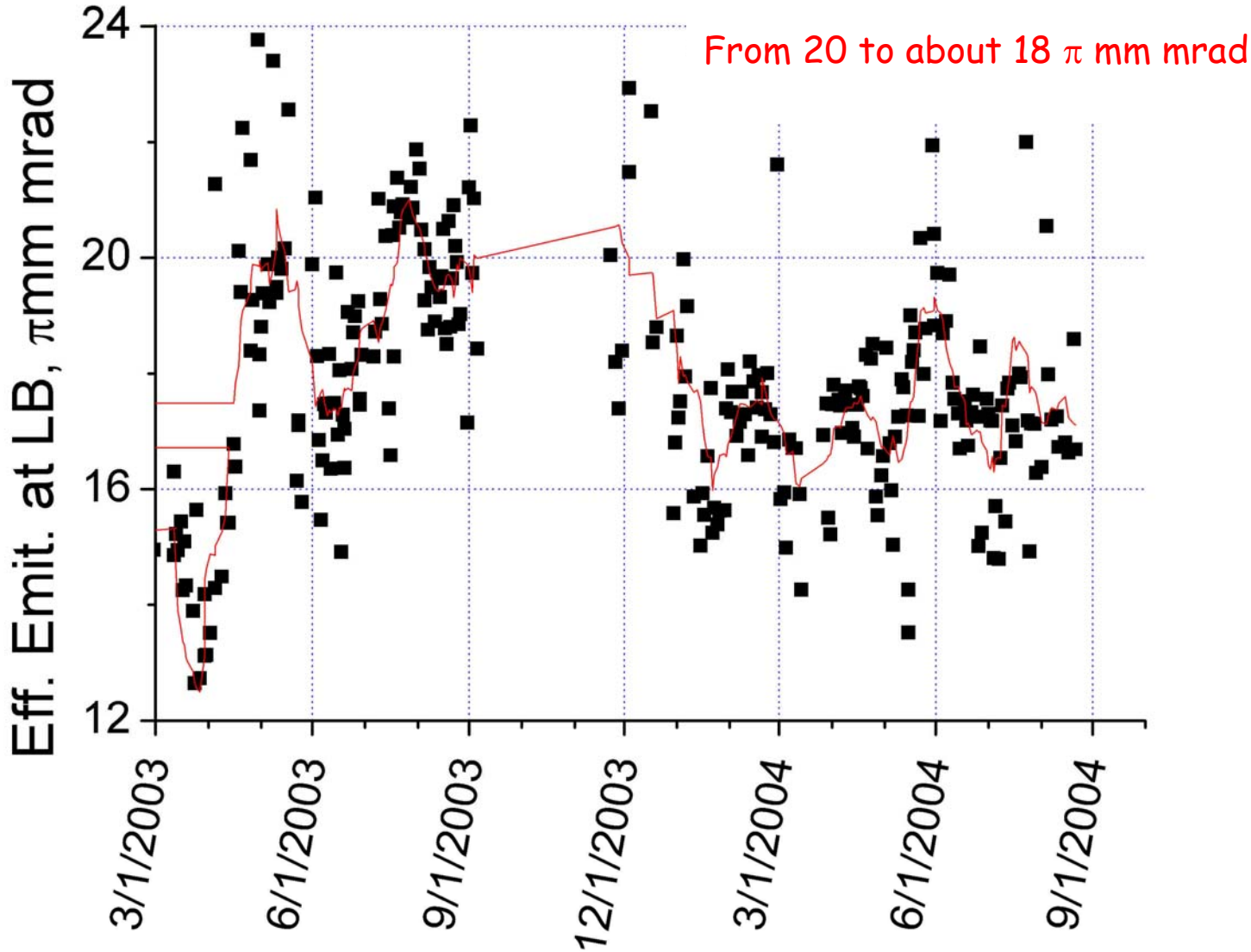
TD team

- Smaller currents in skew corrector circuits:
  - SQ -15%
  - SQA0 -21%
  - SQA4, B1 → 0 A
- -4 pi PVert at Injection

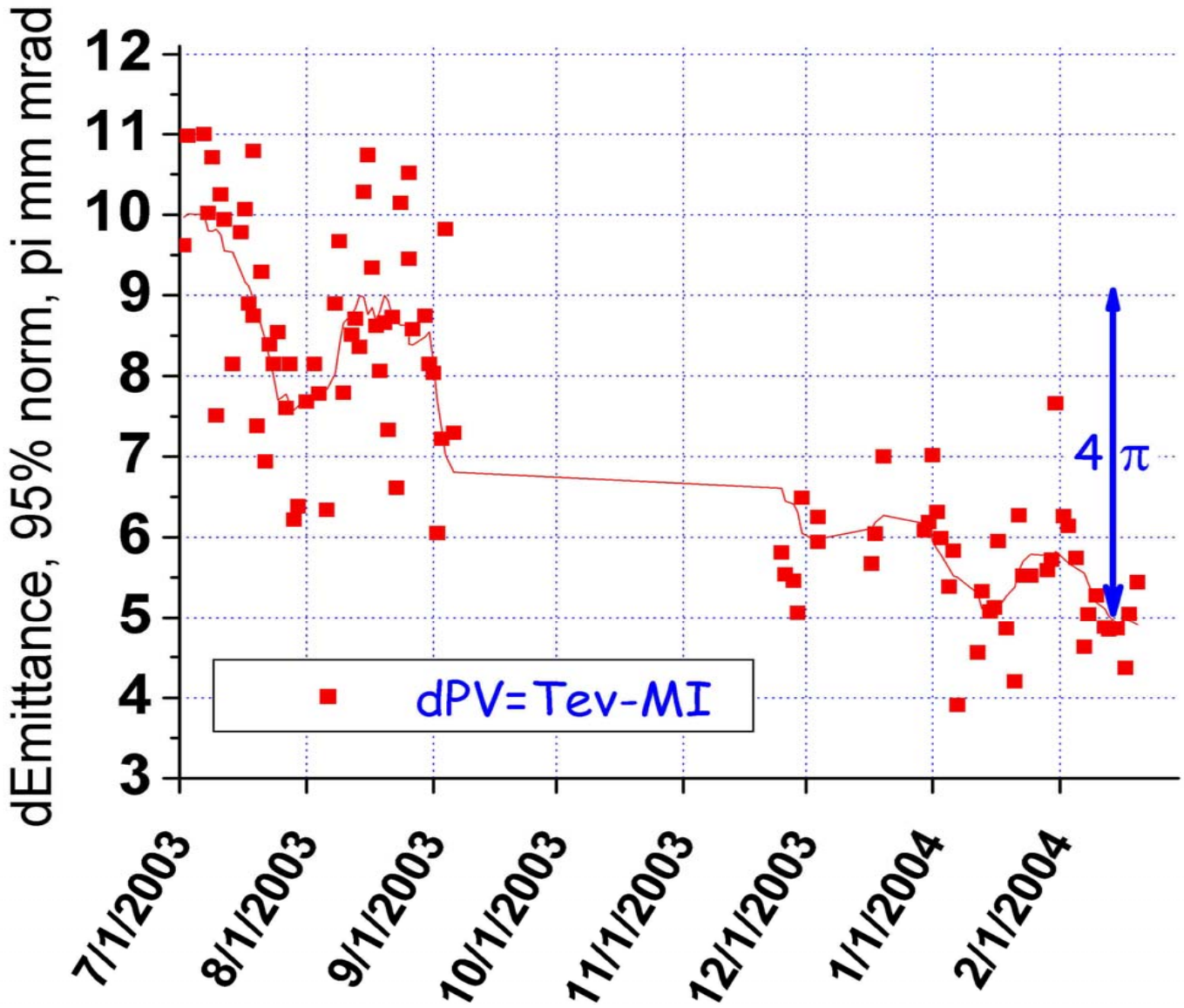
# Emittance Dilution in MI→Tev Transfer



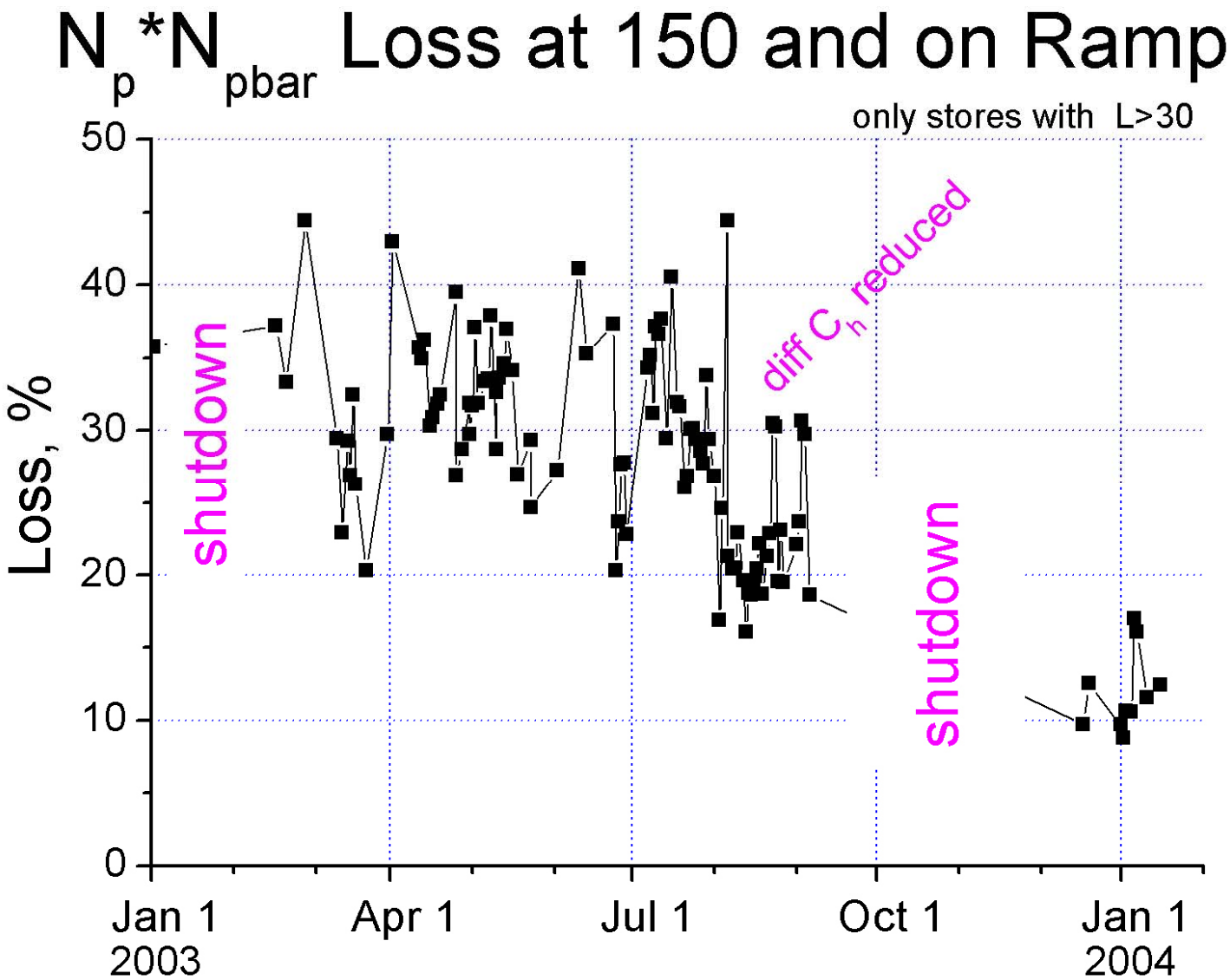
# Seen Well in Luminosity



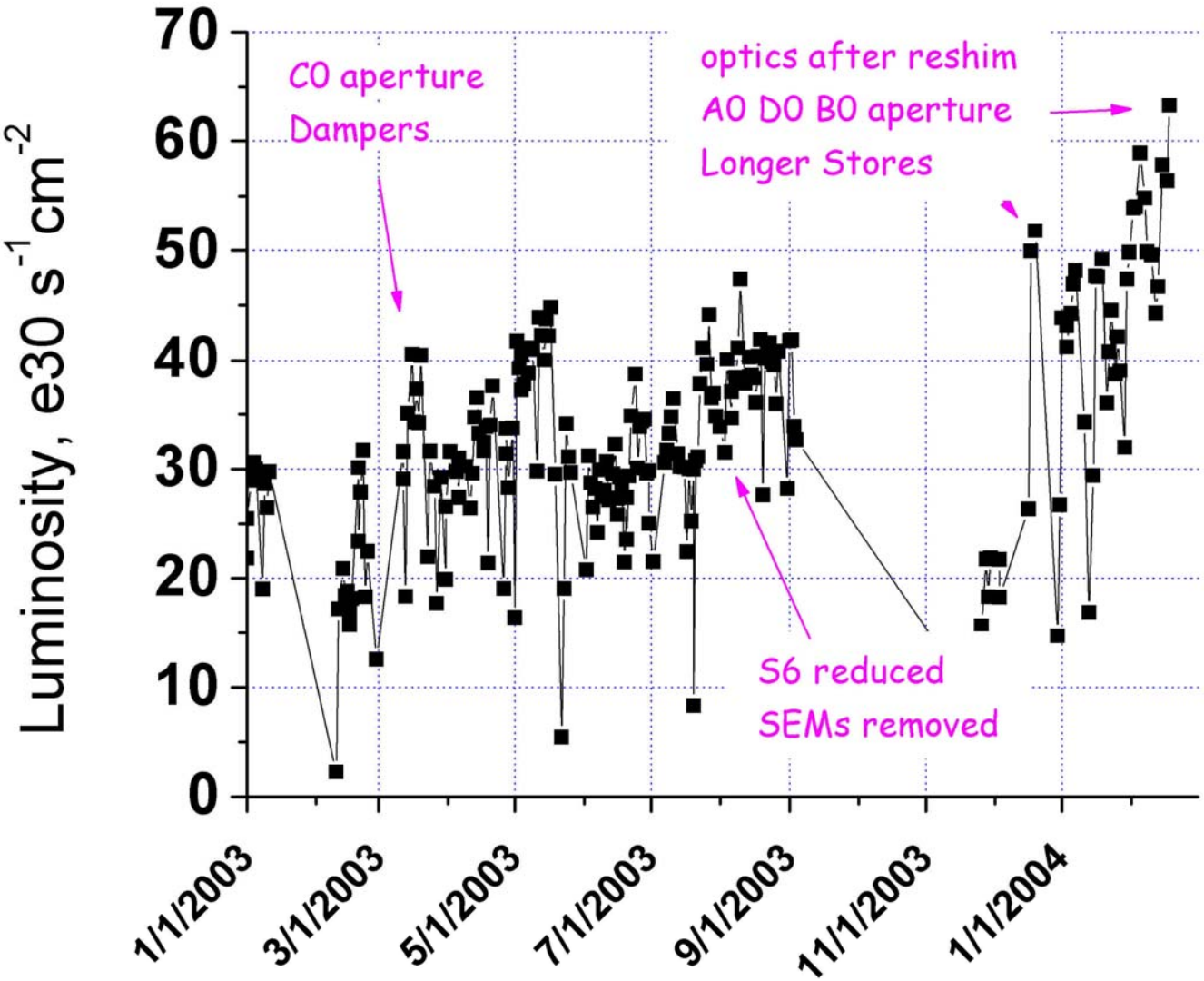
# Reduced Emittance Dilution at Injection



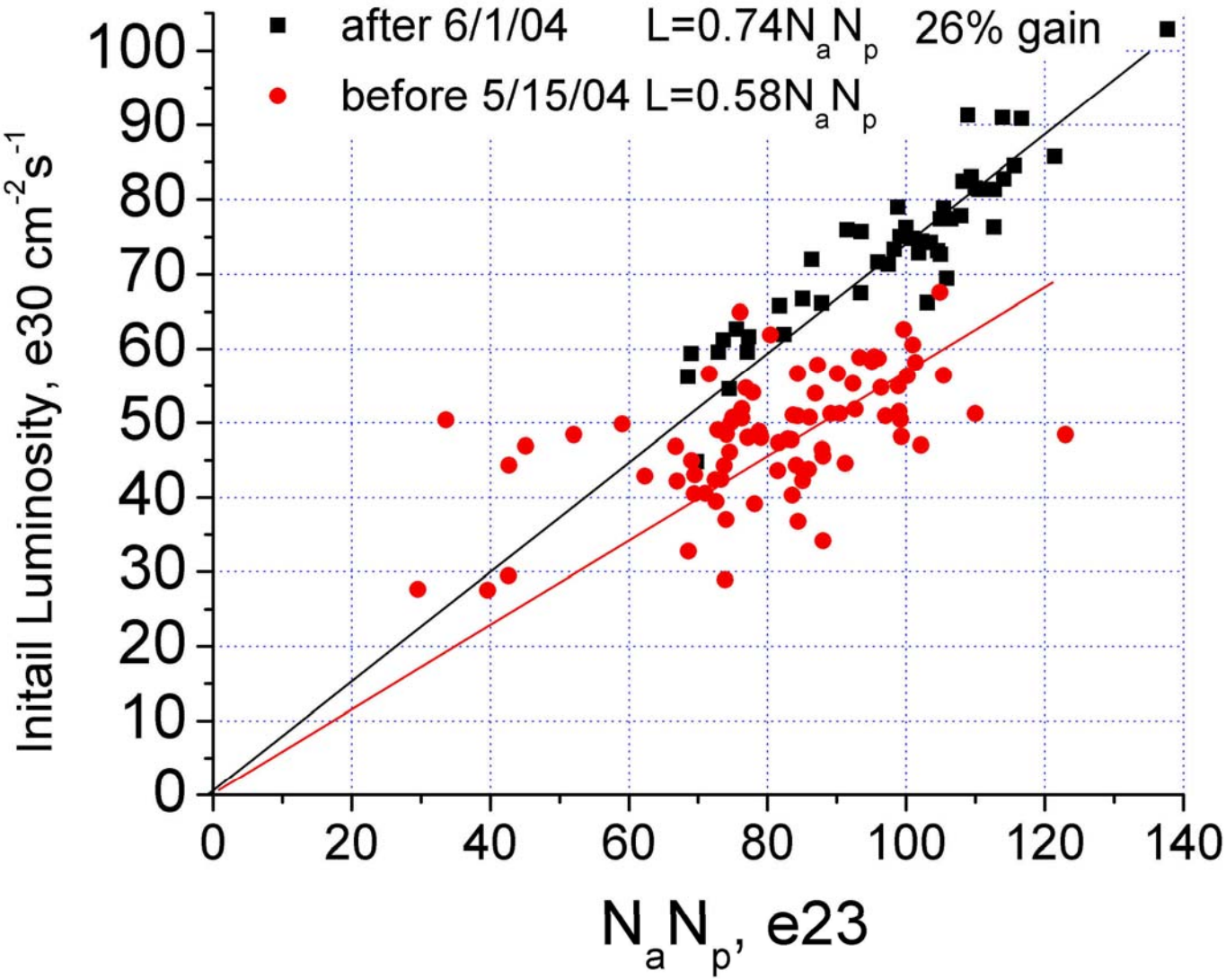
# Larger Aperture+Smaller Emm →Better Efficiency



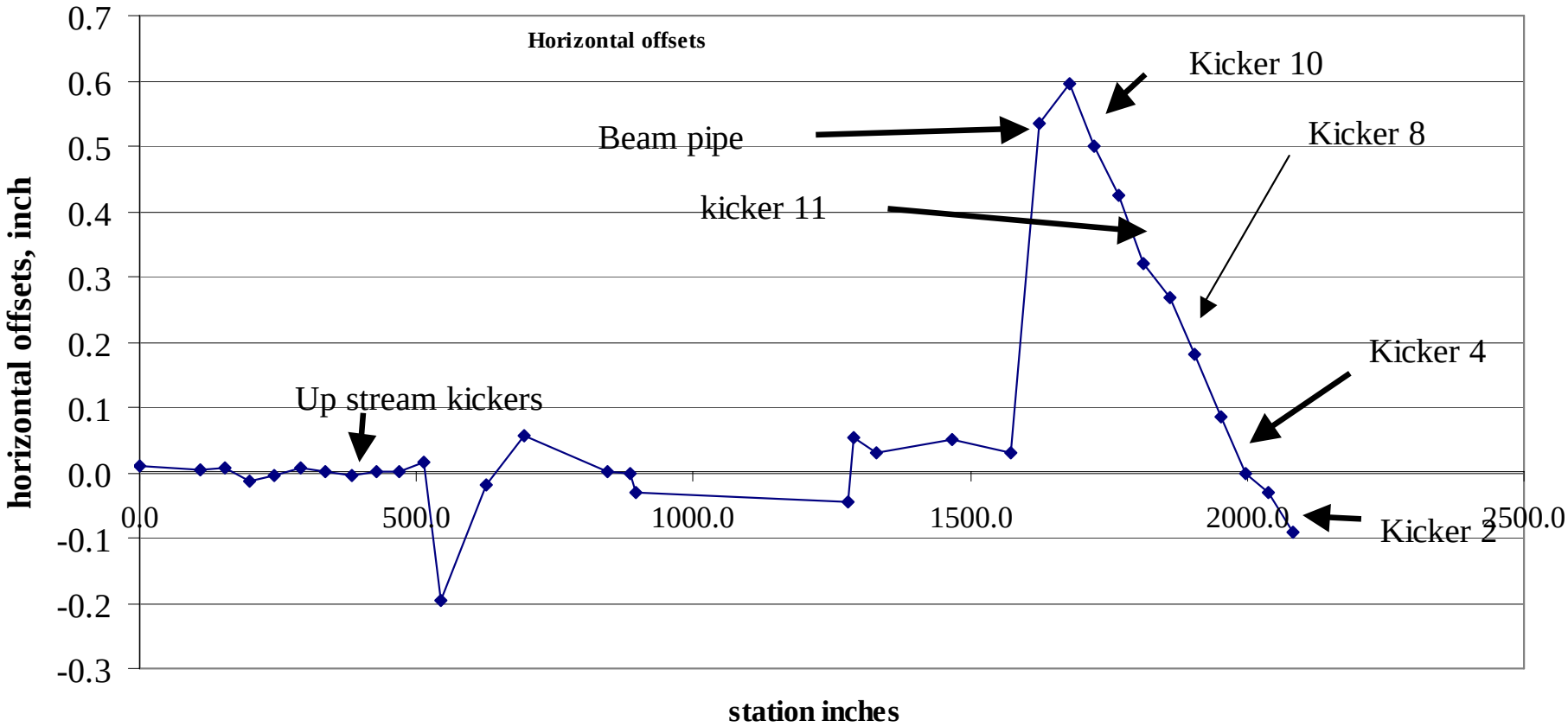
# Tevatron Luminosity Progress



# …and You Get 26% in Peak Luminosity



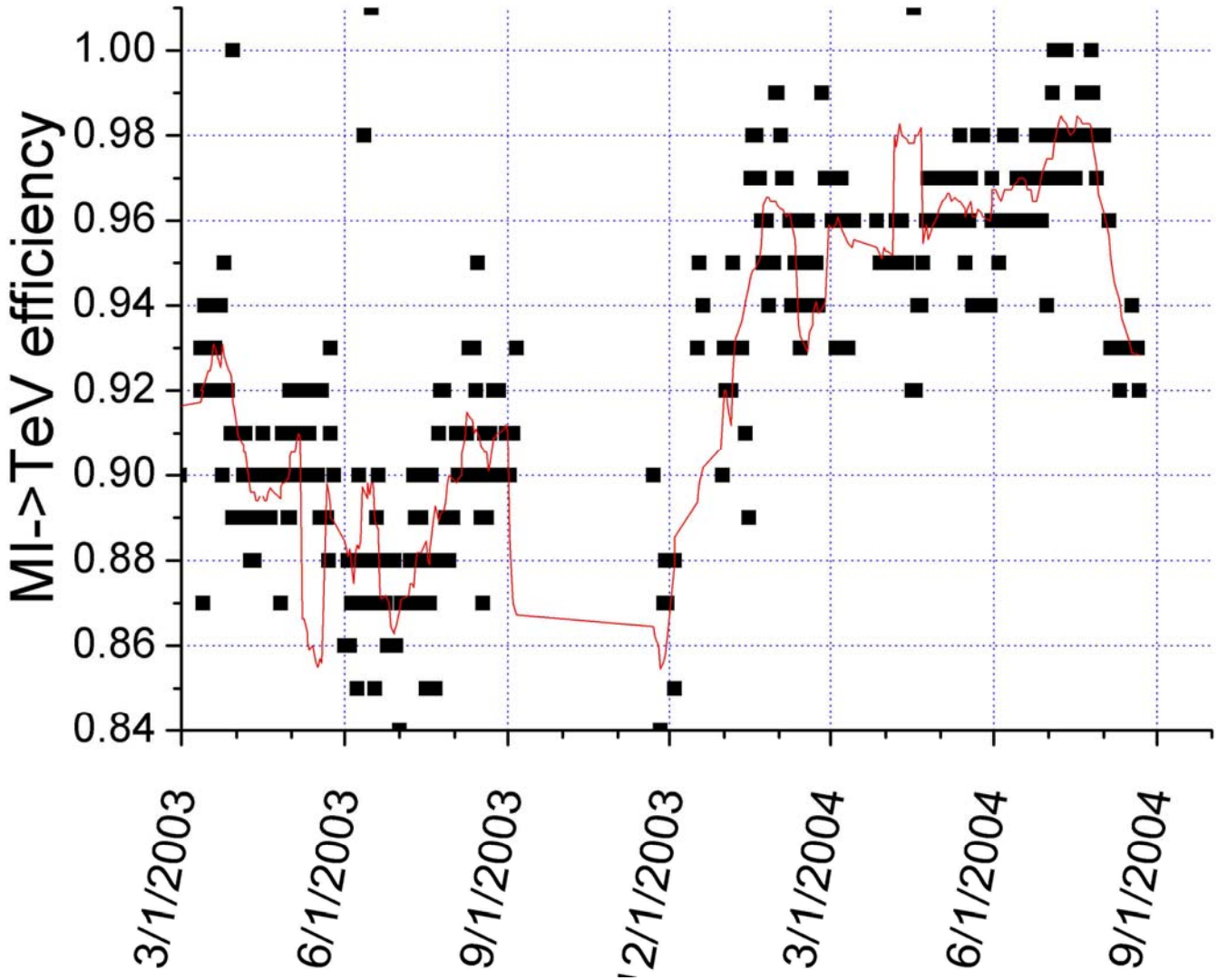
# Alignment: Open Apertures




- Another ¼" misalignment fixed at D0
- Rolls >2mrad ~complete
- # of dipole correctors running >35A out of 50A: 26 → 6

# Alignment: What it really means…

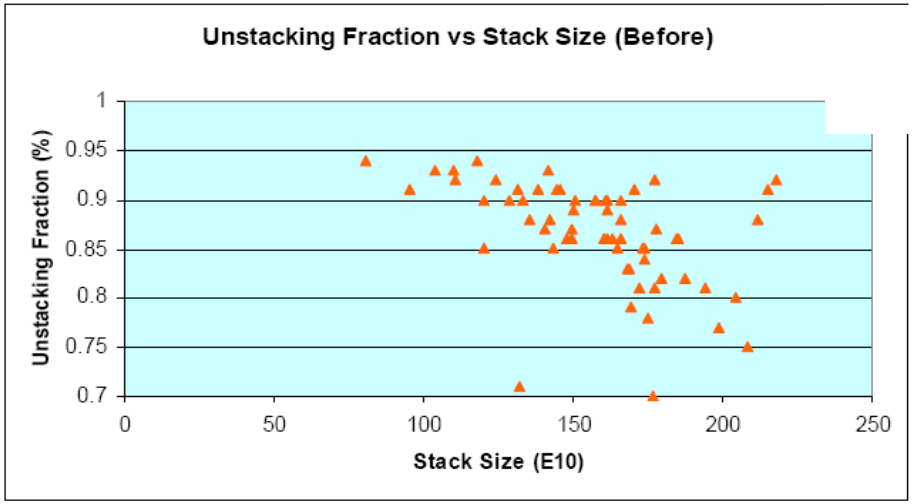
# All That Pays Off in Transfer Efficiency

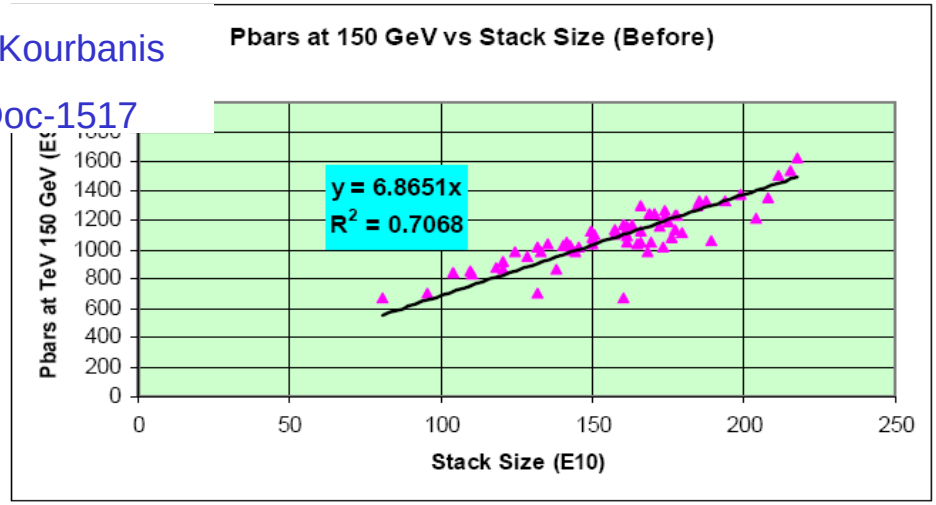


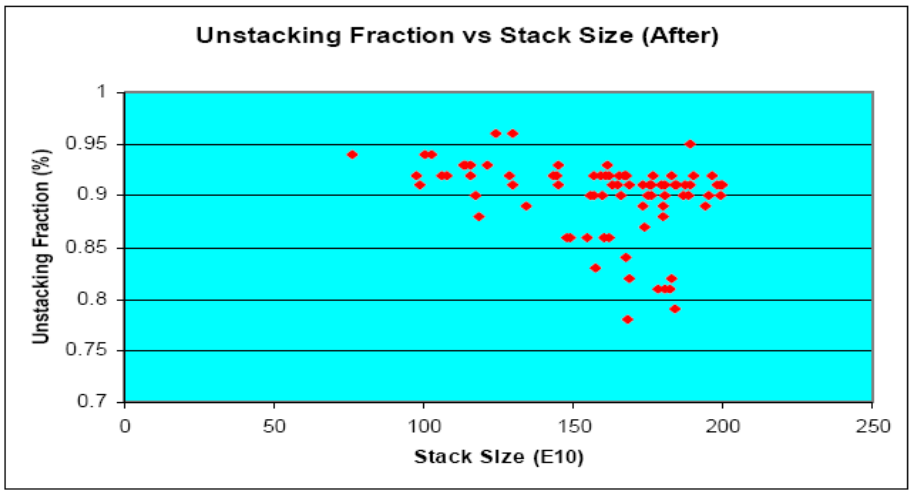
# 2.5 MHz Transfers: 8% more pbars

I.Kourbanis

Doc-1517



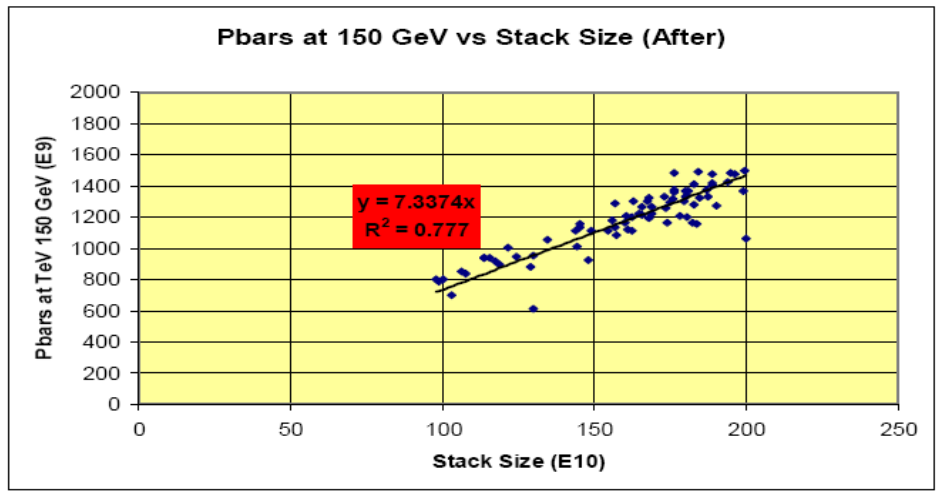
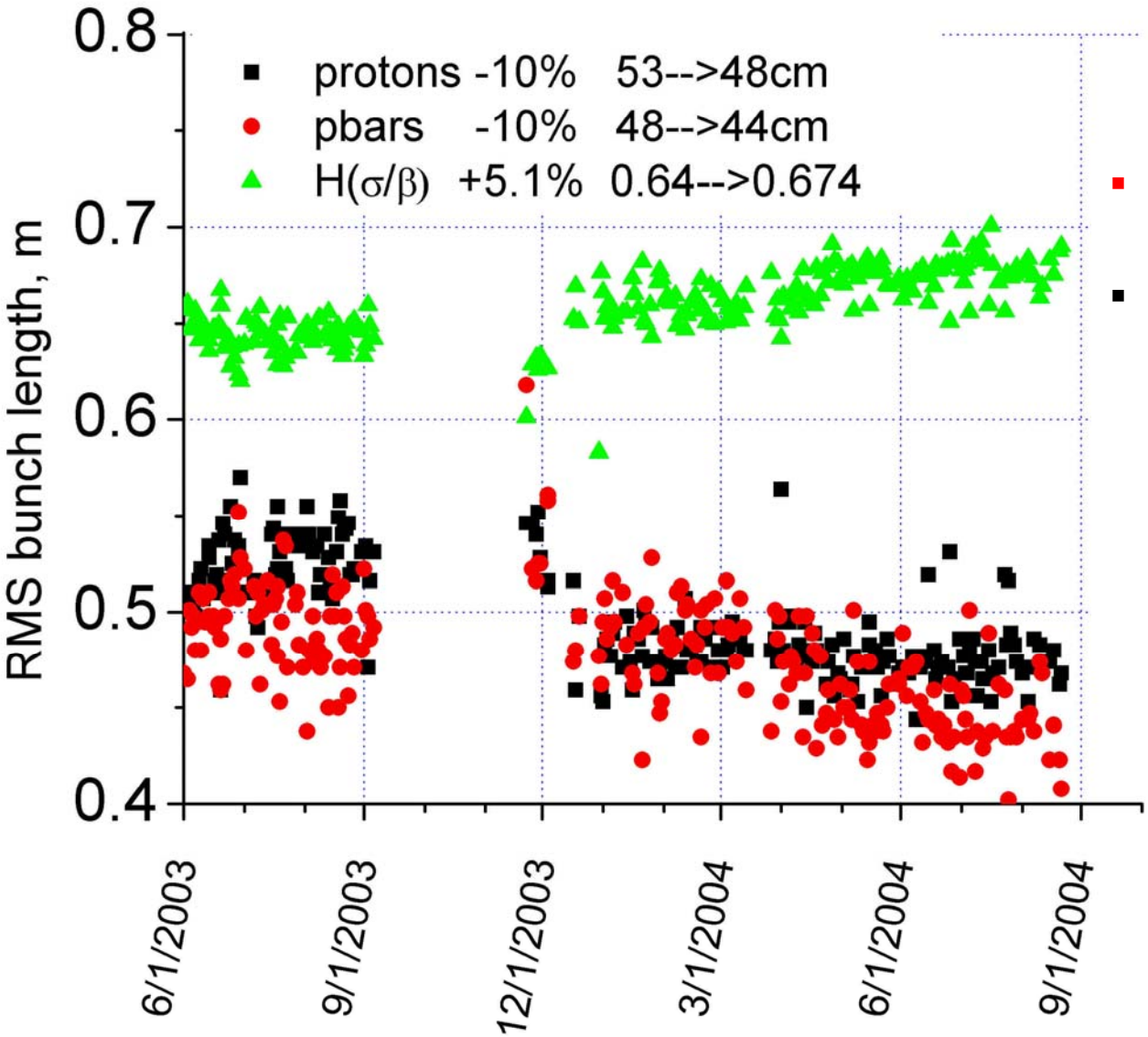




Fig. 5: Unstacking fraction vs. Stack Size for Before the 2.5 MHz pbar Transfers and after

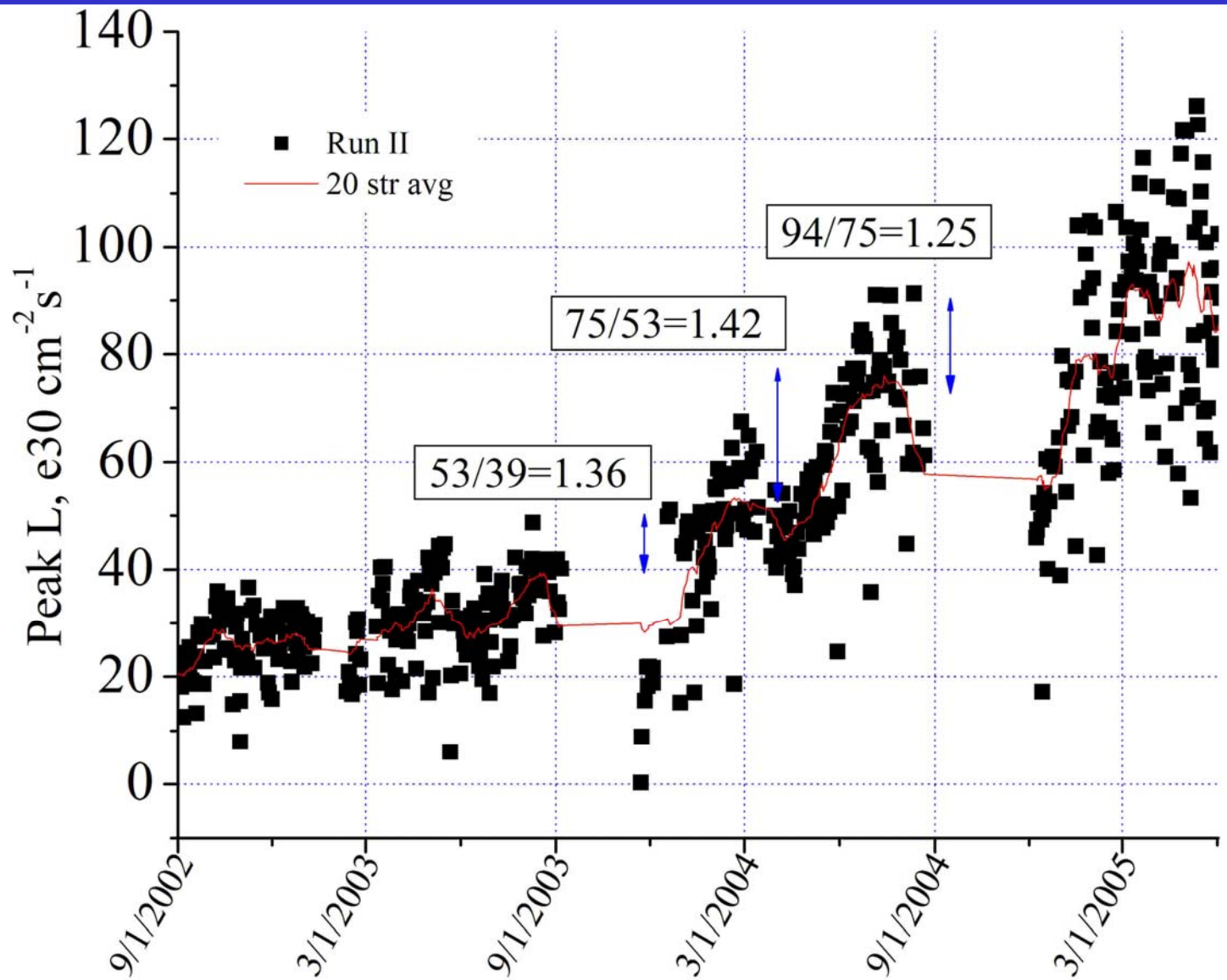
Fig. 6: Pbars at TeV Injection as a function of Pbar Stack Size Before (top) and after (bottom) the 2.5 MHz pbar transfers.

# MI Studies Shortens Bunchlength → +5%

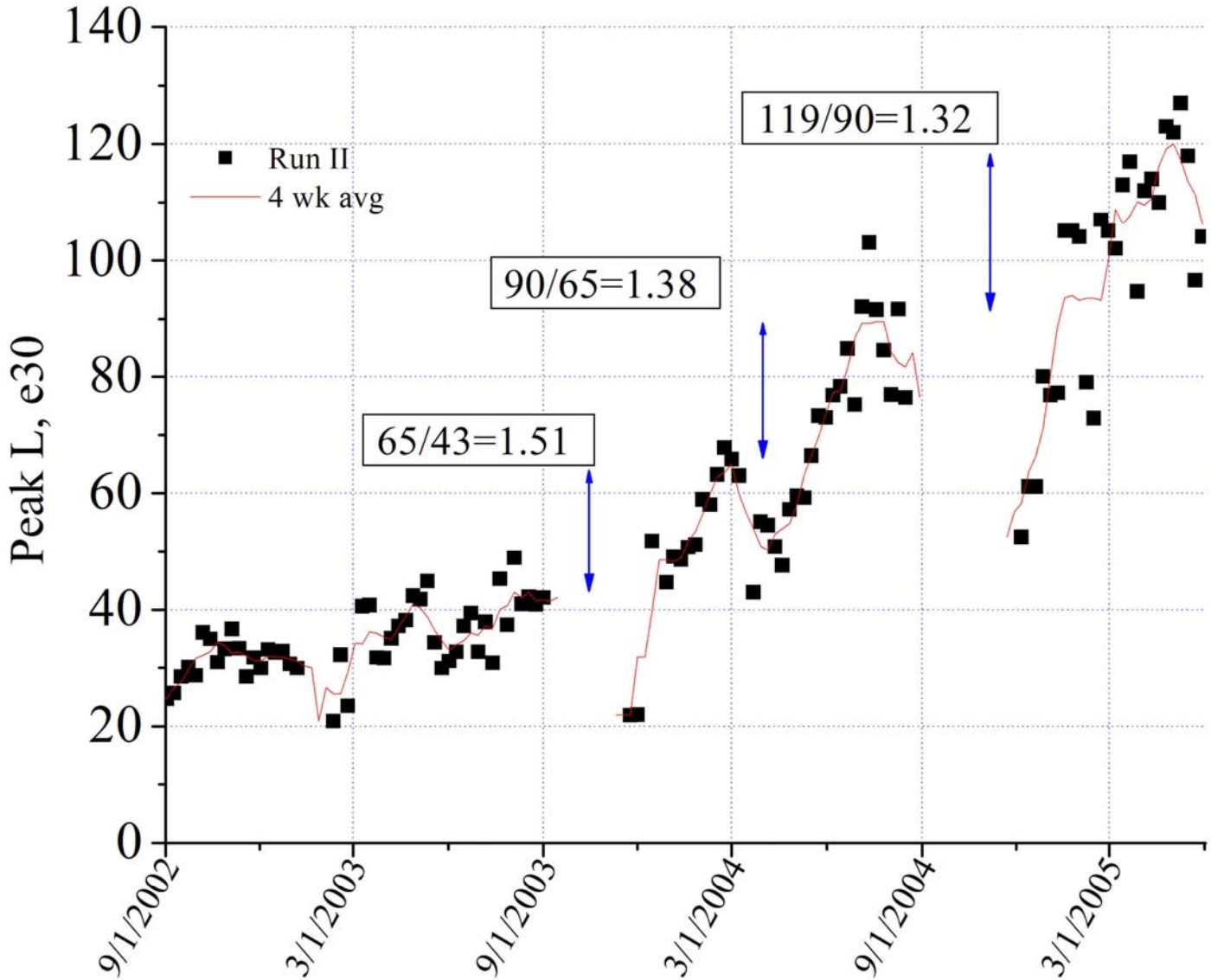



- 2.5 MHz transfers of pbars from AA to MI
- Beam loading compensation and longitudinal instability damper for protons

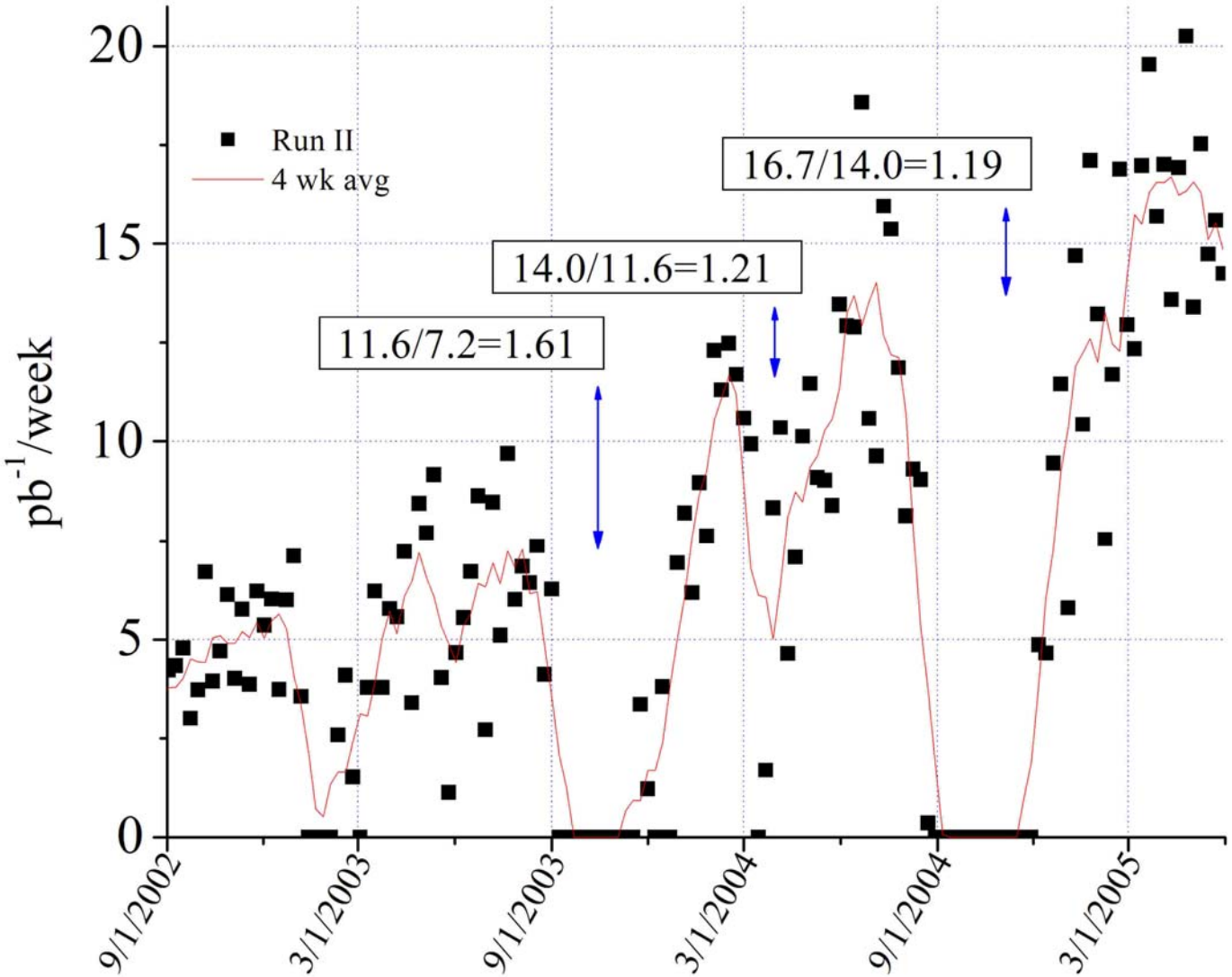
# Peak Luminosity progress since 09/2002



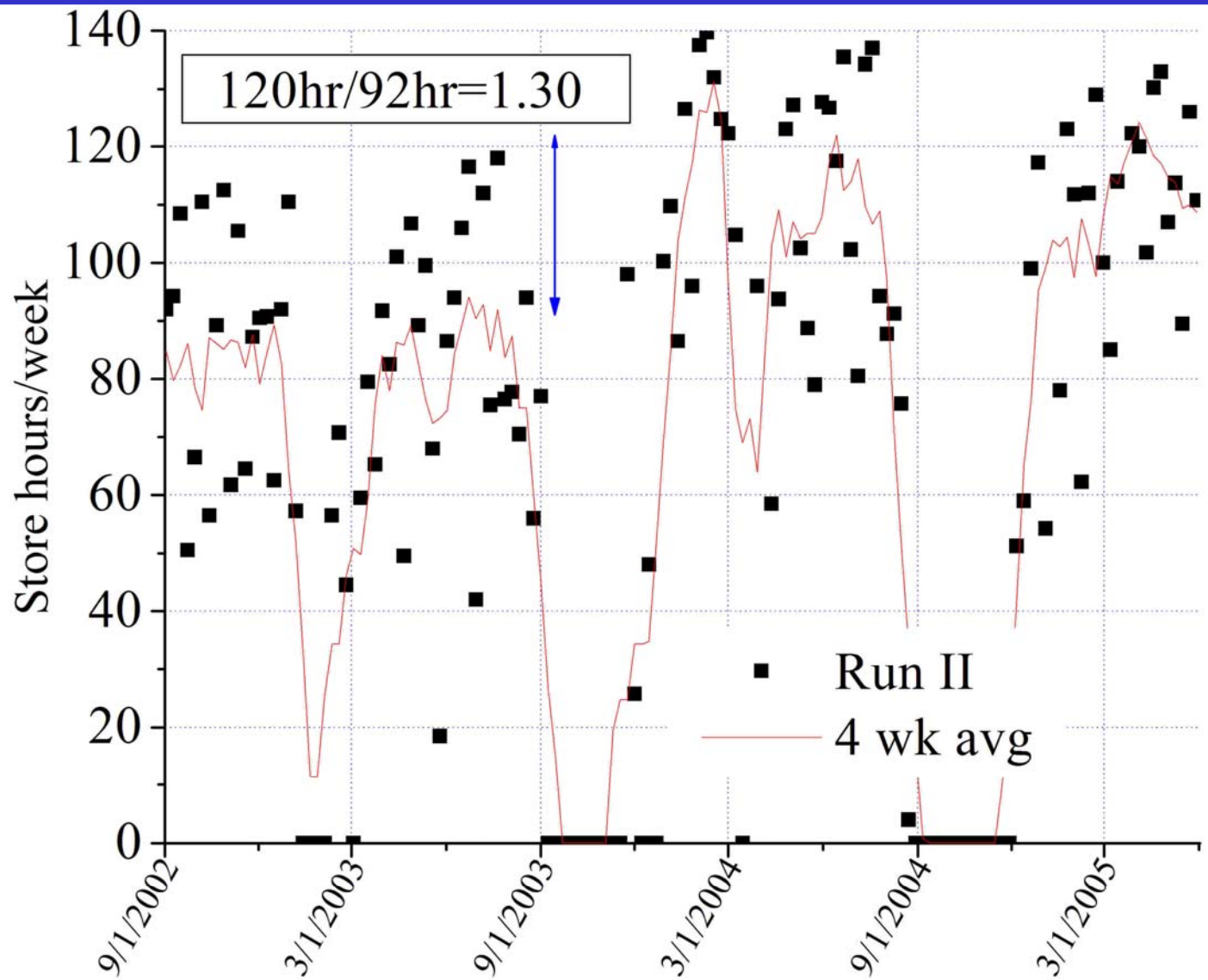
# Maximum Peak Luminosity progress since 09/2002



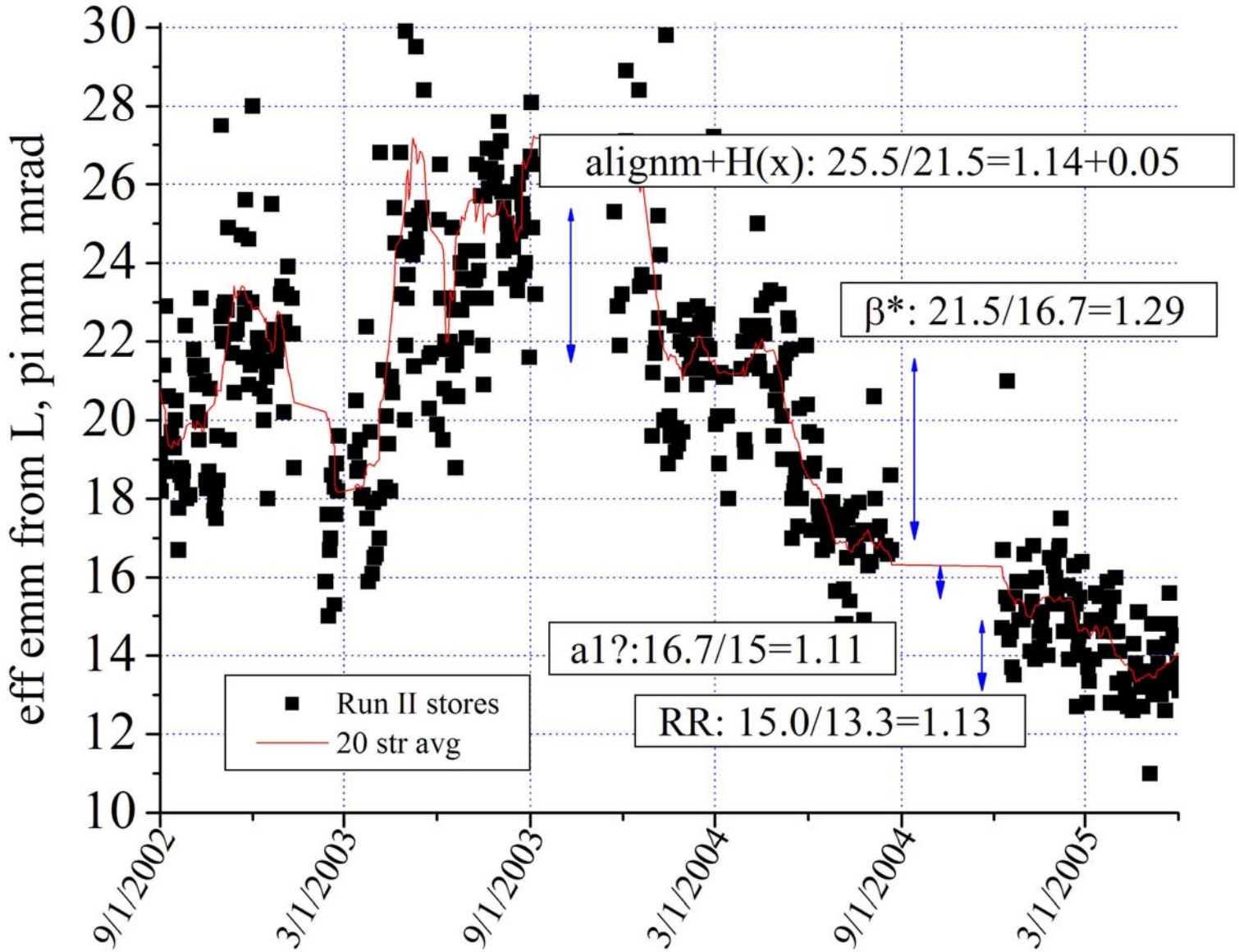
# Integrated Luminosity per week



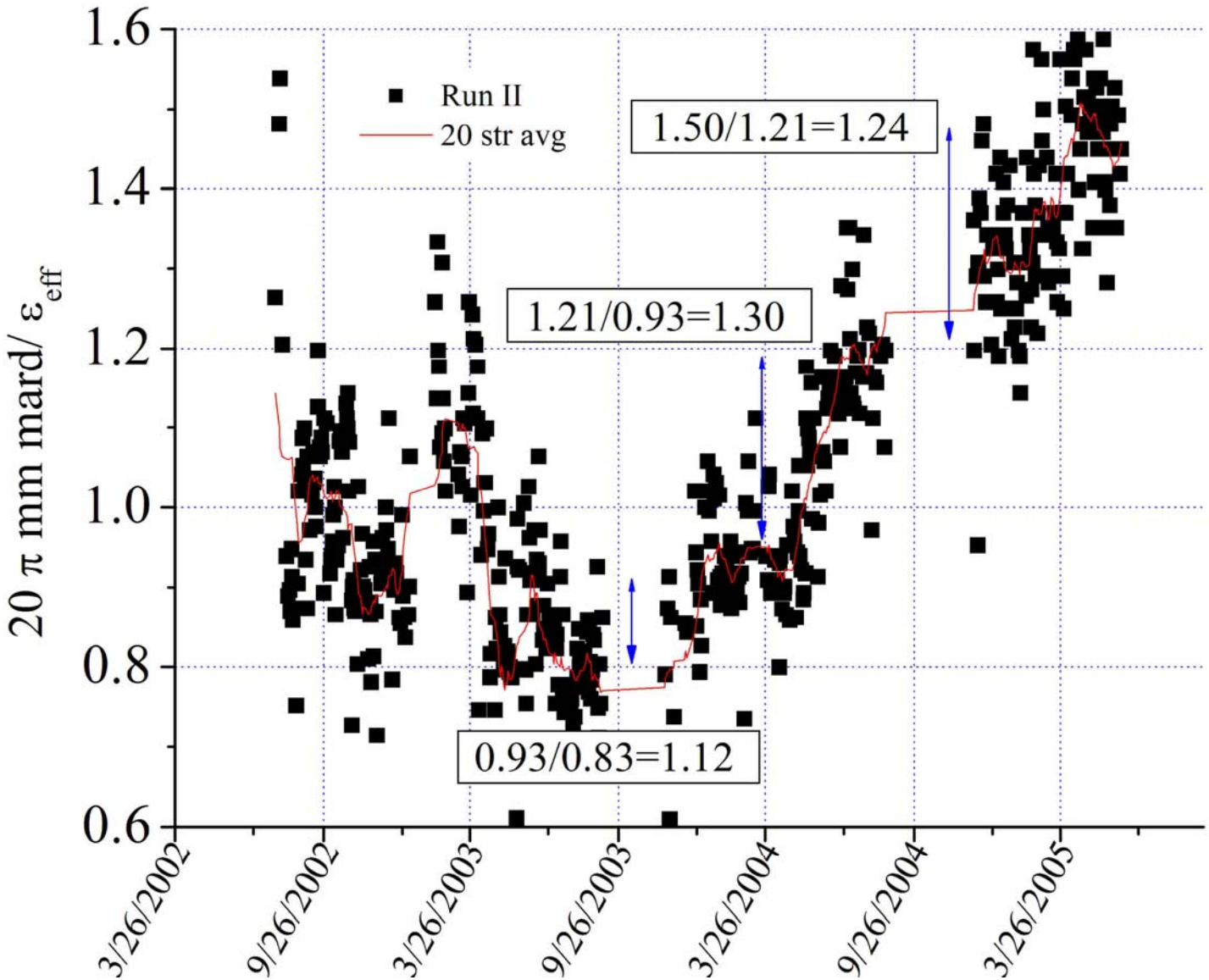
# Store Hours/ wk in Run II



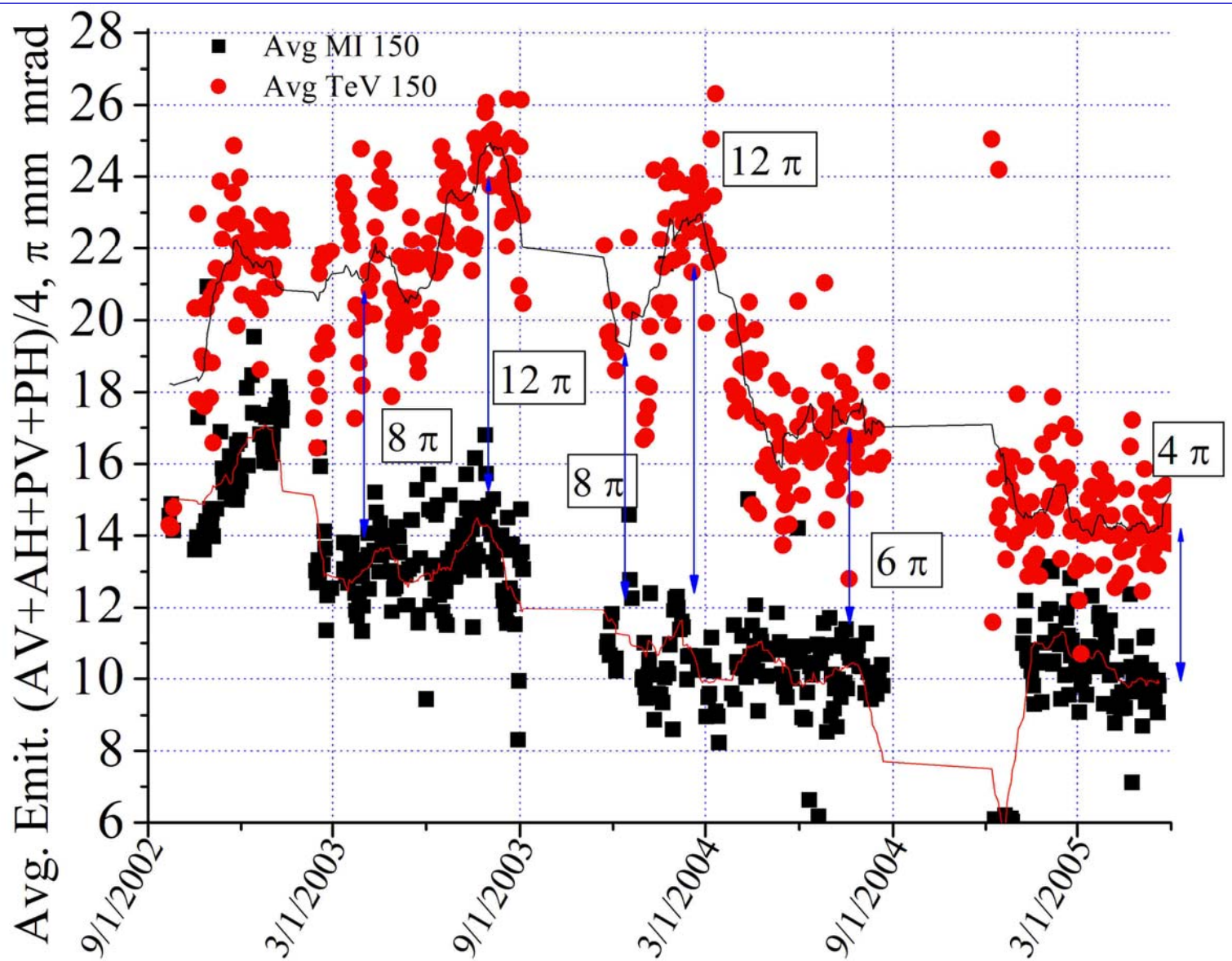
# Effective Emittance from Luminosity



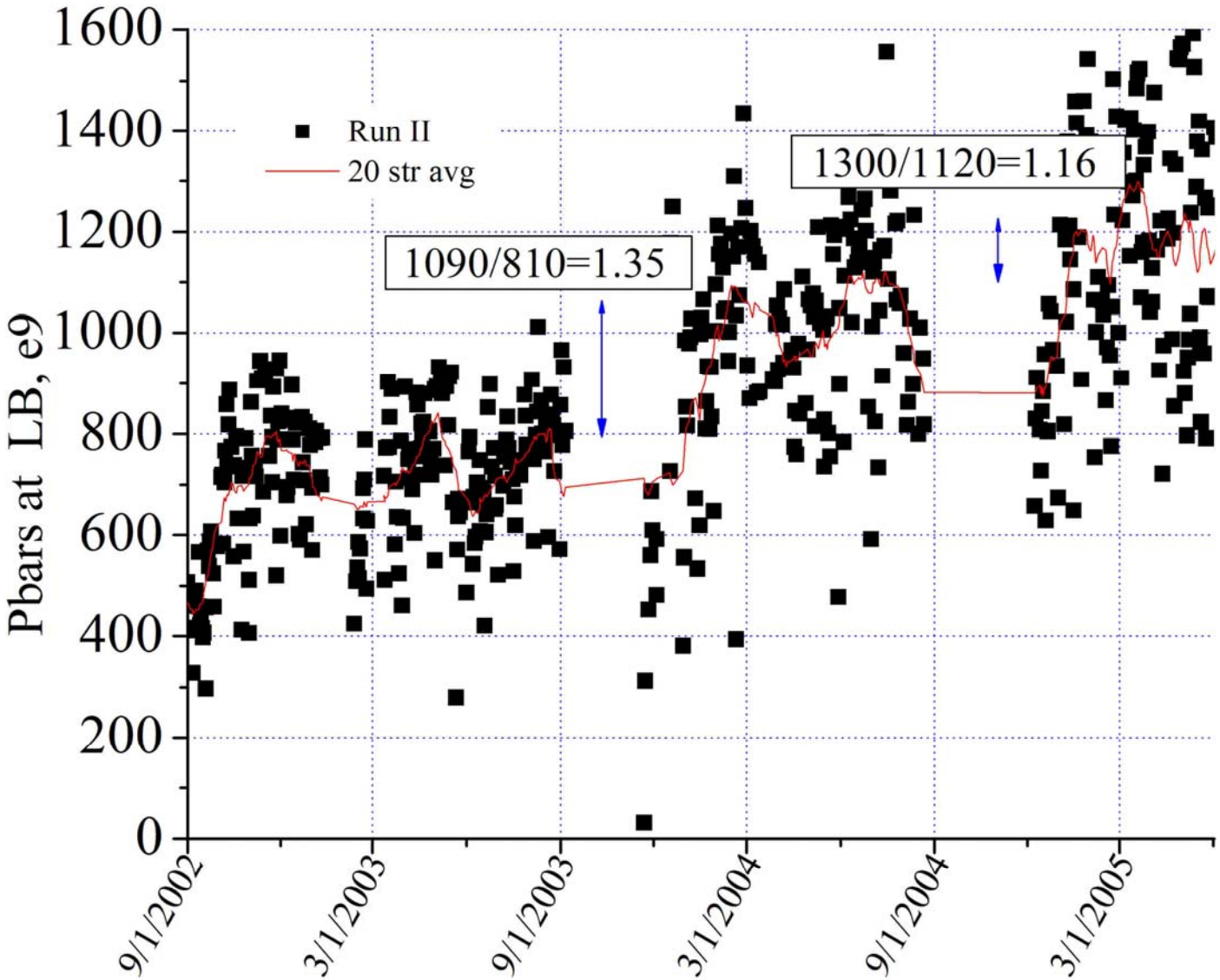
# 1/Effective Emittance from Luminosity



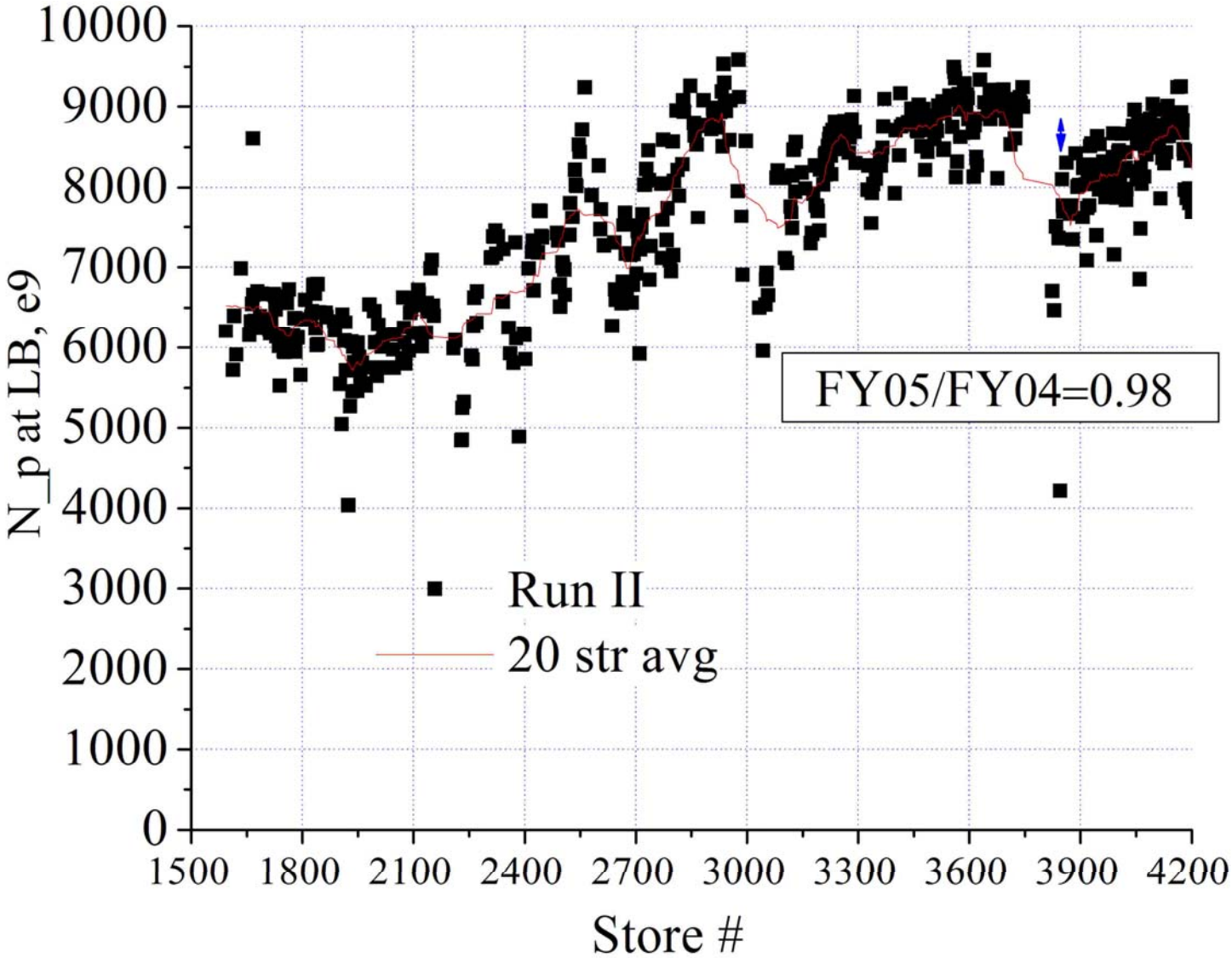
# 150 GeV Emittance from FW: TeV vs MI



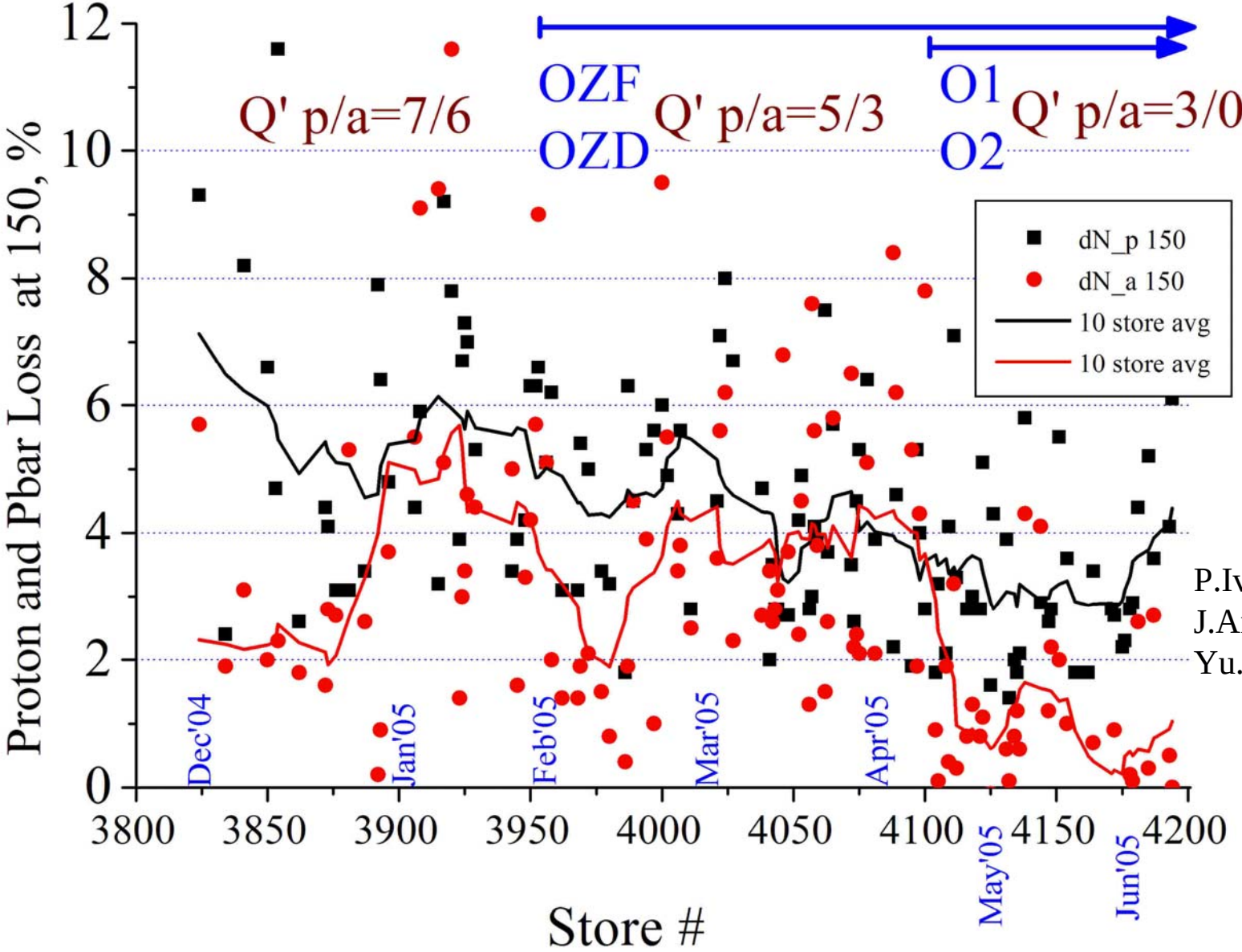
# Pbars at Low Beta in Run II (Run Ib=540e9)



# P's at Low Beta in Run II (Run Ib equiv 10000e9)

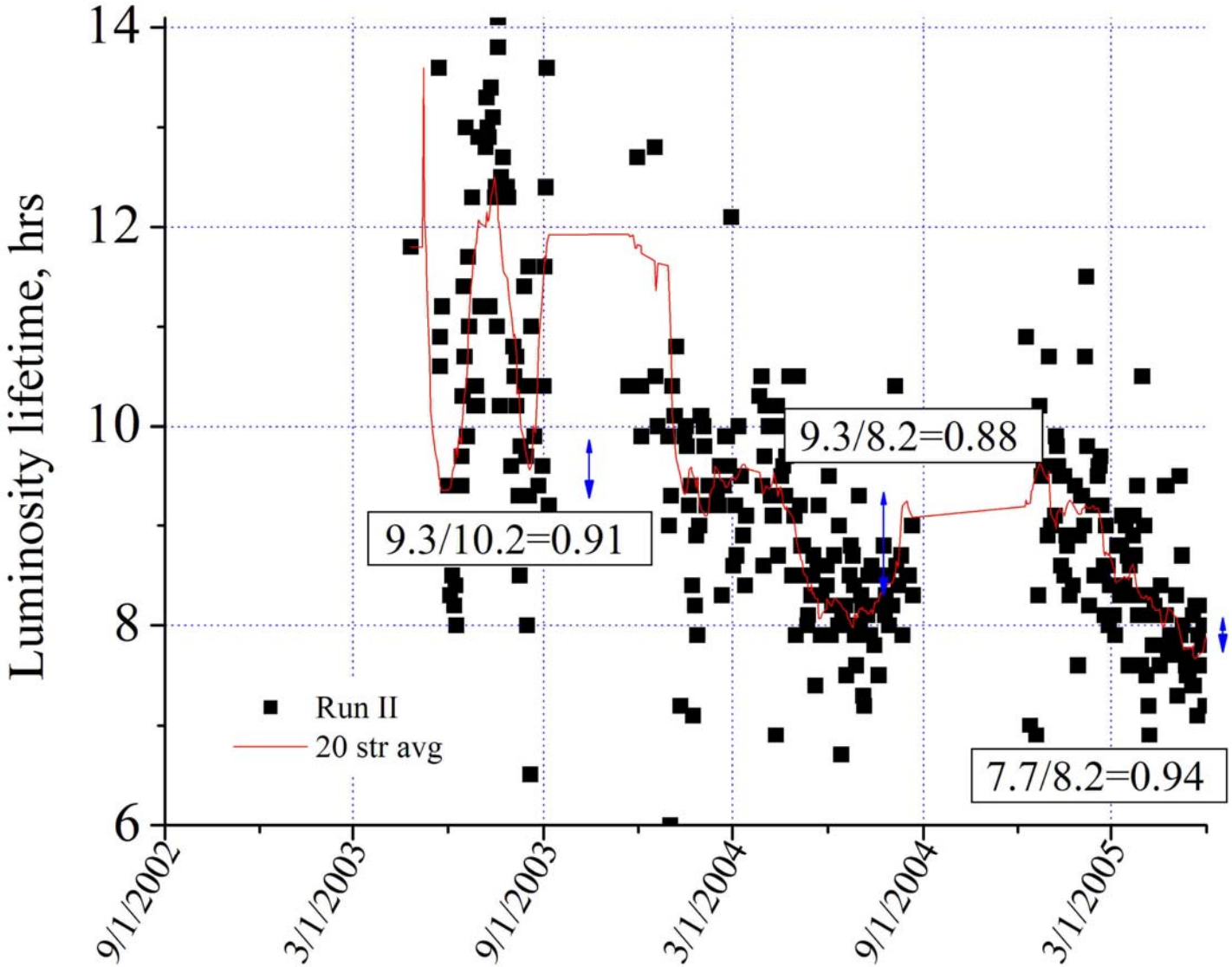


# Octupoles to Drop Chromaticity Q'=dQ/(dp/p)

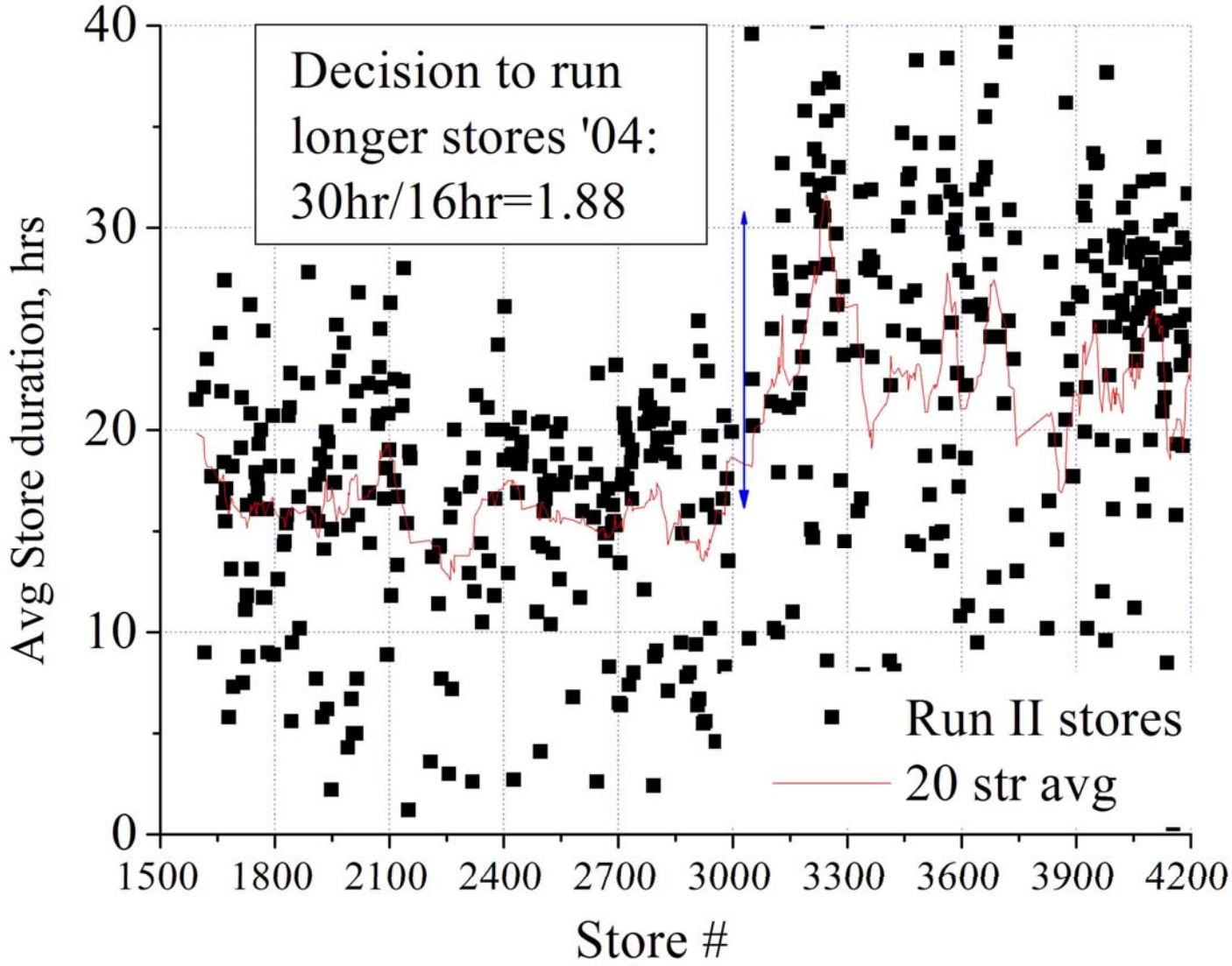



P.Ivanov
J.Annala
Yu.Alexahin

# Luminosity Lifetime since 09/2002



# Average Store Duration



# $\mathcal{L}$-progress '02 – '03

| | | | |
|---|---|---|---|
| "Sequence 13" fixed | Tev | Spring'02 | x 1.40 |
| "New-new" injection helix | Tev | Summer'02 | x 1.15 |
| "Shot lattice" | AA | Summer'02 | x 1.40 |
| Pbar emittance at injection | Tev/Lines | Fall'02 | x 1.20 |
| Pbar coalescing improved | MI | Fall'02 | x 1.15 |
| C0 Lambertson removal | Tev | Feb'03 | x 1.15 |
| S6 in Tev and SEMS in AP | Tev&AA | July'03 | x 1.15 |

….plus additional improvements in the Tevatron:

- Tunes/coupling/chromaticities at 150/ramp/LB
- Orbit smoothing
- Longitudinal damper to stop $\sigma_s$ blowup
- Transverse dampers improve 150 Gev lifetime
- Separator scans

# $\mathcal{L}$-progress: Shutdown '03 – March '04

| | Peak L | Int L | N_a | N_p | Emm_eff | RunTime |
|---|---|---|---|---|---|---|
| ▪ Total progress | 1.51 | 1.61 | 1.35 | 0.98 | 1.12 | 1.37 |
| ➢ Tev reshim | 12% | 9% | | | 12% | |
| ➢ 2.5MHz MI | 8% | 5% | 8% | | | |
| ➢ Tev dampers and Align | 5% | 3% | 4% | 2%? | | |
| ➢ StoreTime/Length | 19% | 19+16% | 21% | | -2%? | 37% |

# $\mathcal{L}$-progress: Mar'04 – Jul '04

| | Peak L | Int L | N_a | N_p | Emm_eff | RunTime |
|---|---|---|---|---|---|---|
| ▪ Total progress | 1.41 | 1.21 | 1.02 | 1.02 | 1.30 | 0.92 |
| ➢ Tev beta* | 29% | 20%? | | | 29% | |
| ➢ BmLoad MI | 5% | 4%? | | | 5% in H(x) | |
| ➢ Reliability | | -8% | | | | |

# $\mathcal{L}$-progress: Shutdown '04 – June '05

| | Peak L | Int L | N_a | N_p | Emm_eff | Store T |
|---|---|---|---|---|---|---|
| ▪ Total progress | 1.32 | 1.19 | 1.16 | 0.98 | 1.24 | 1.0 |
| ➢ No Tev precycle | | 2% | | | | |
| ➢ Tev octupoles | 7% | 5% | 4% | 3% | | |
| ➢ RR mixed shots | 25% | 11% | 12% | | 13% | |
| ➢ ?(Tev Align/reshim) | | 5%? | | | 11% ? | ???? |

*WARNING!:*

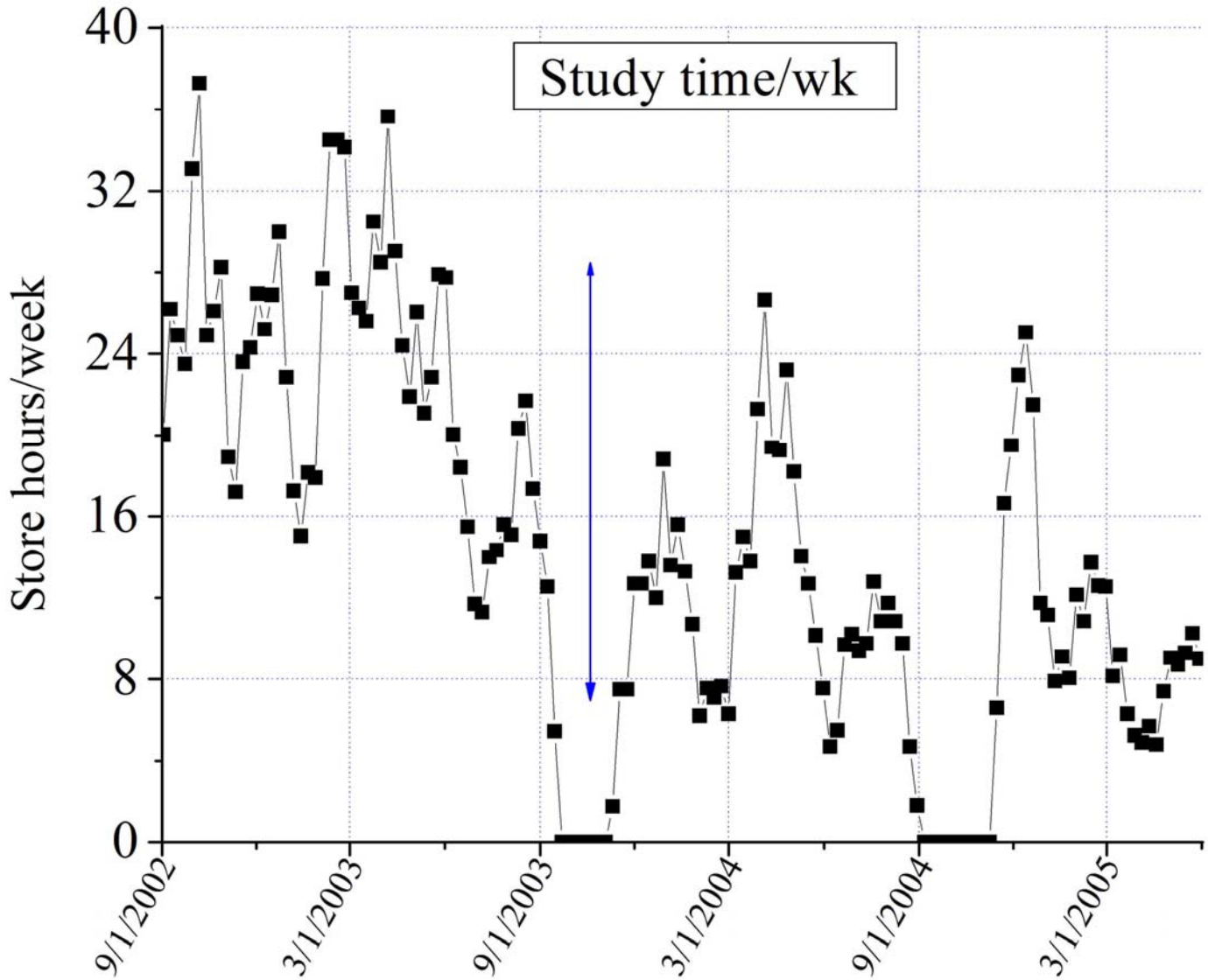
*a) Error bars: +- 1 % for 2% effects*

*+- 3 % for 10% effects*

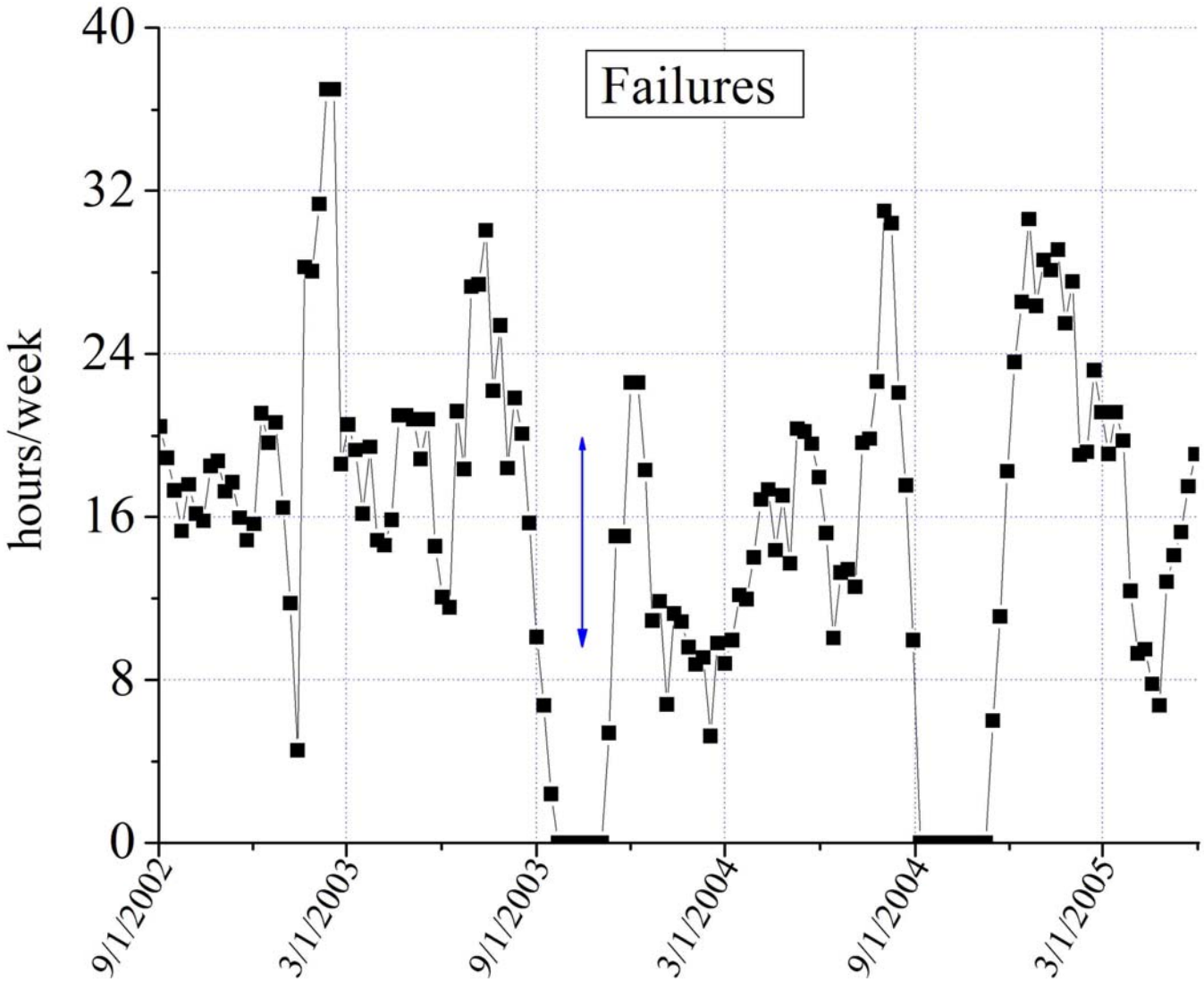
*+- 5 % for 30-50% effects*

*b) "One man" vision & analysis*

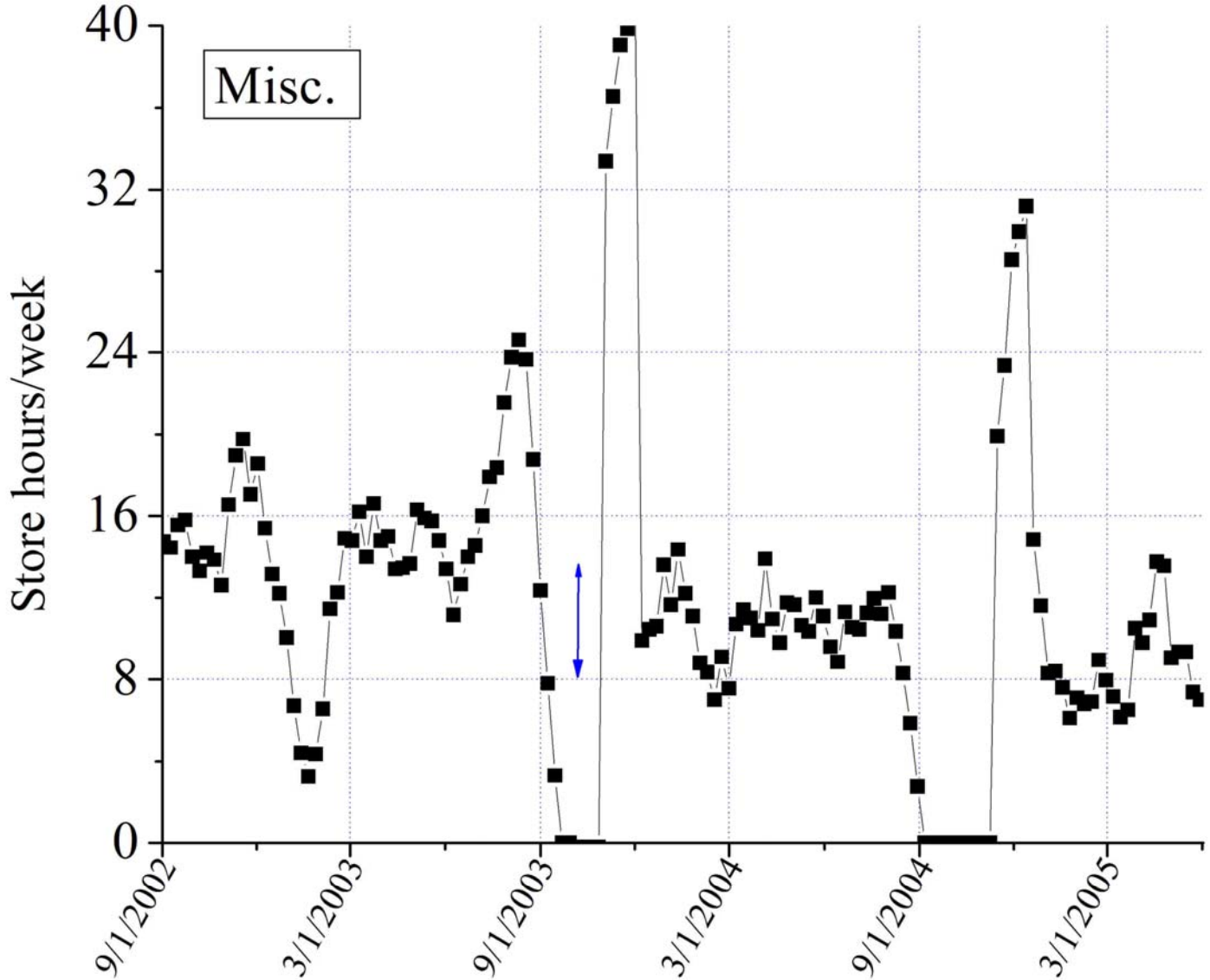
# Study time hrs/wk since 09/2002



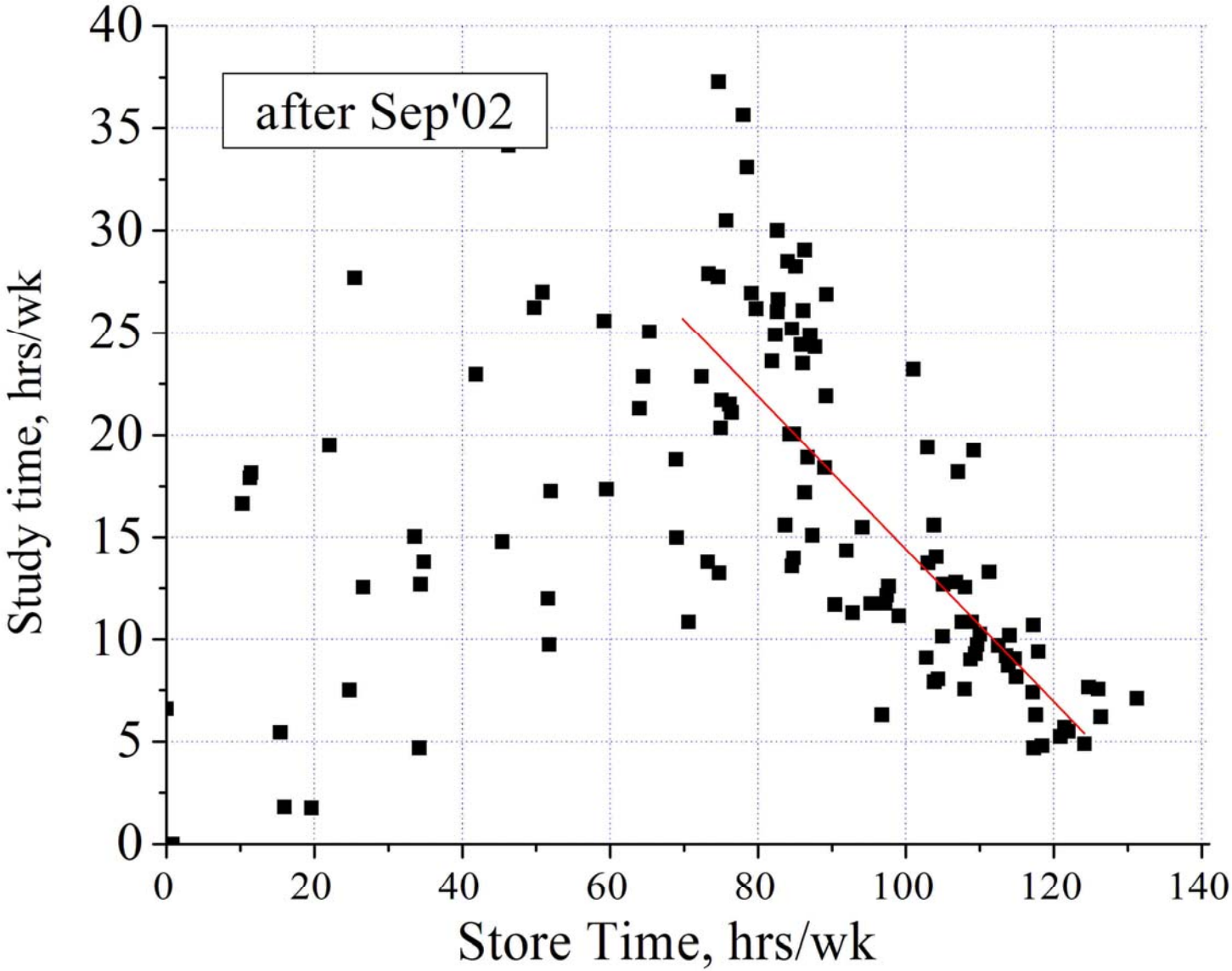
# Failure (hrs/week): Tev failures, quench recovery, etc



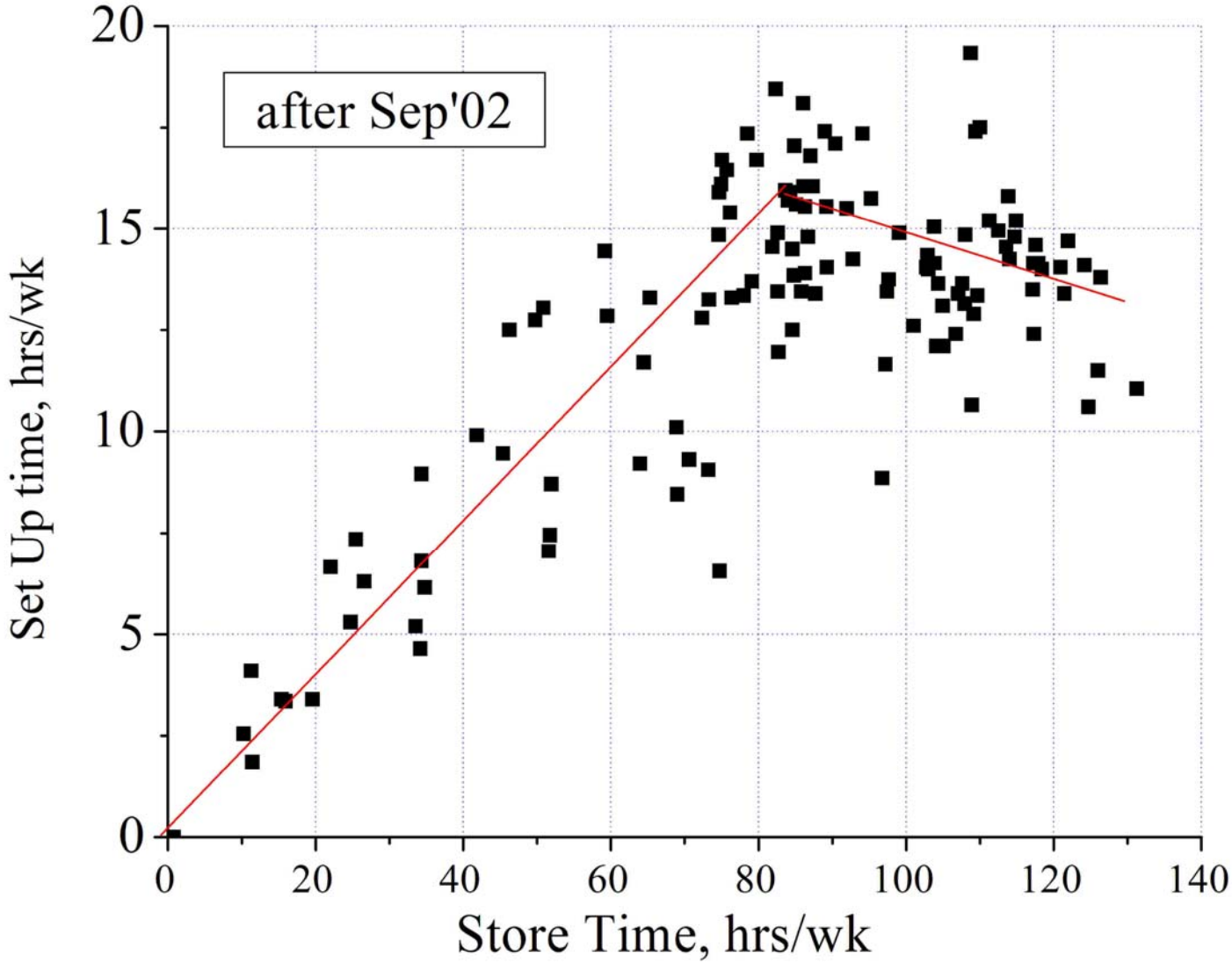
# "Misc" time= detector access, startup, etc



# Study time vs Store Hours/wk



# Shot SetUp time vs Store Time/wk



# Conclusions: I

- From Summer'03 to Summer'05, peak luminosity has grown by factor 2.8 (40→120e30) and weekly integrated luminosity by factor 2.3 (7.2→16.7 pb-1/wk)
- Most important improvements (>10%) came from:

| | L_peak | L_int | |
|---|---|---|---|
| ➢ RR mixed shots | 25% | 11% | studies |
| ➢ Beta* change | 29% | 20% | studies |
| ➢ MI 2.5MHz/BLC | 13% | 9% | studies |
| ➢ Reliability/L-time | 19% | 36% | management |
| ➢ Tev Reshim/Align | 12% | 9% | shutdown |

  with additional detectable/recognizable contributions due to Tev octupoles, Tev precycle elimination, and Tev instability dampers

- Open question whether there was real emittance improvement in MI → TeV transfers after FY'04 shutdown

# Conclusions II

- (Depending on above) Operation of the Recycler in "mixed source" mode led to 6-11% increase of weekly integrated luminosity in FY'05
- (Un)surprisingly, comparable RR effects come from both smaller emittances of pbar bunches and from higher pbar intensity
- Increase of the running time (+28 hrs) after FY'03 gave one time gain of 36% in luminosity integral. Most of the extra time came from study time reduction (-16hrs), more reliable Tevatron (-8hrs), and shorter "Misc" time (-4 hrs).
- Later in FY'04 and FY'05, the time in collision slipped back –(8..10) hrs, due to worsened reliability (partly compensated by further reduction of study time)
- As expected, statistics shows anticorrelation btw "Store time" (hrs/wk) and "Study" time, and btw "Store" and "SetUp" time

Thanks to Ioanis for emotional discussion on the subject

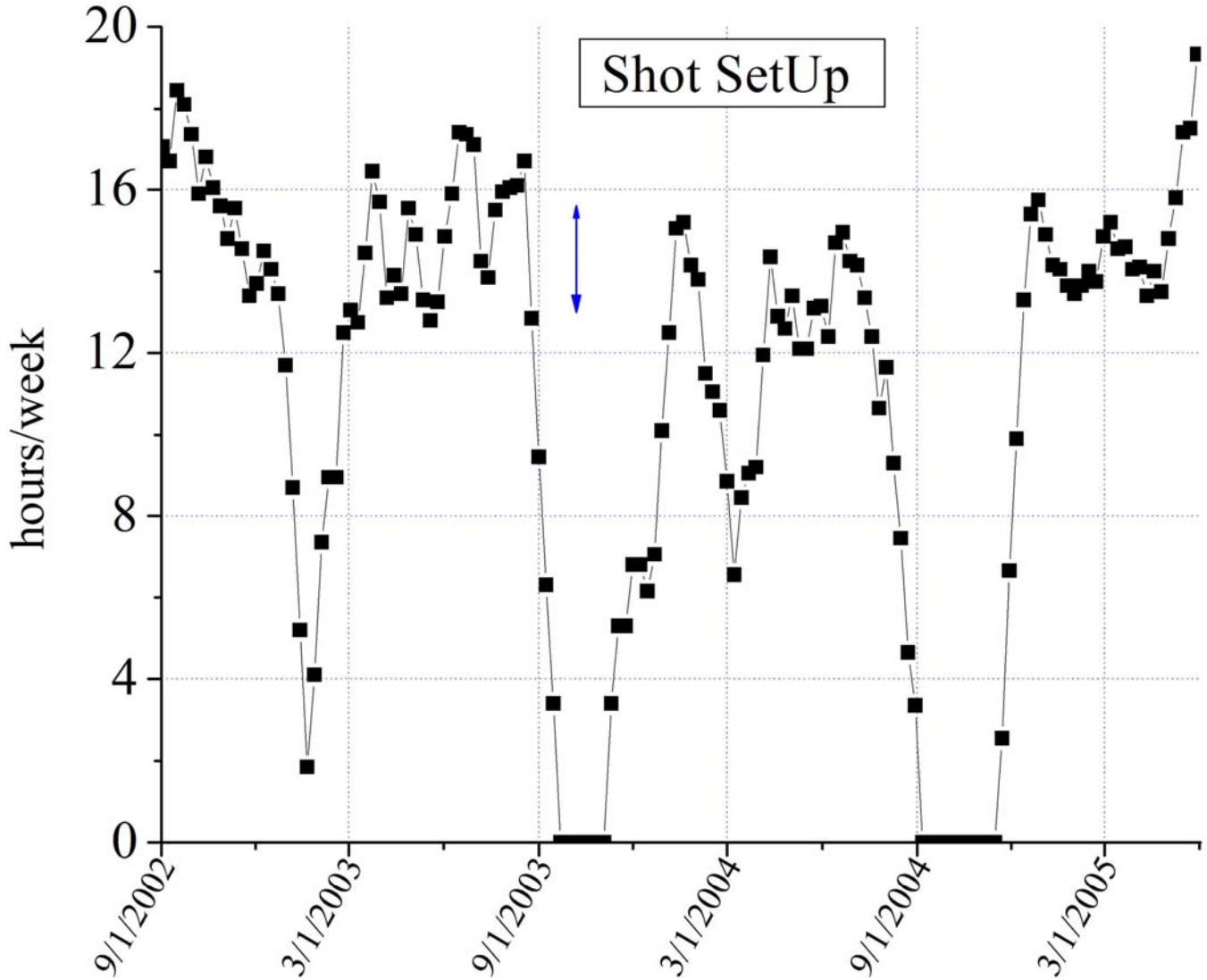
# More open questions

In discussions with Ioanis, Sergei, Cons and JimM several question were raised up:

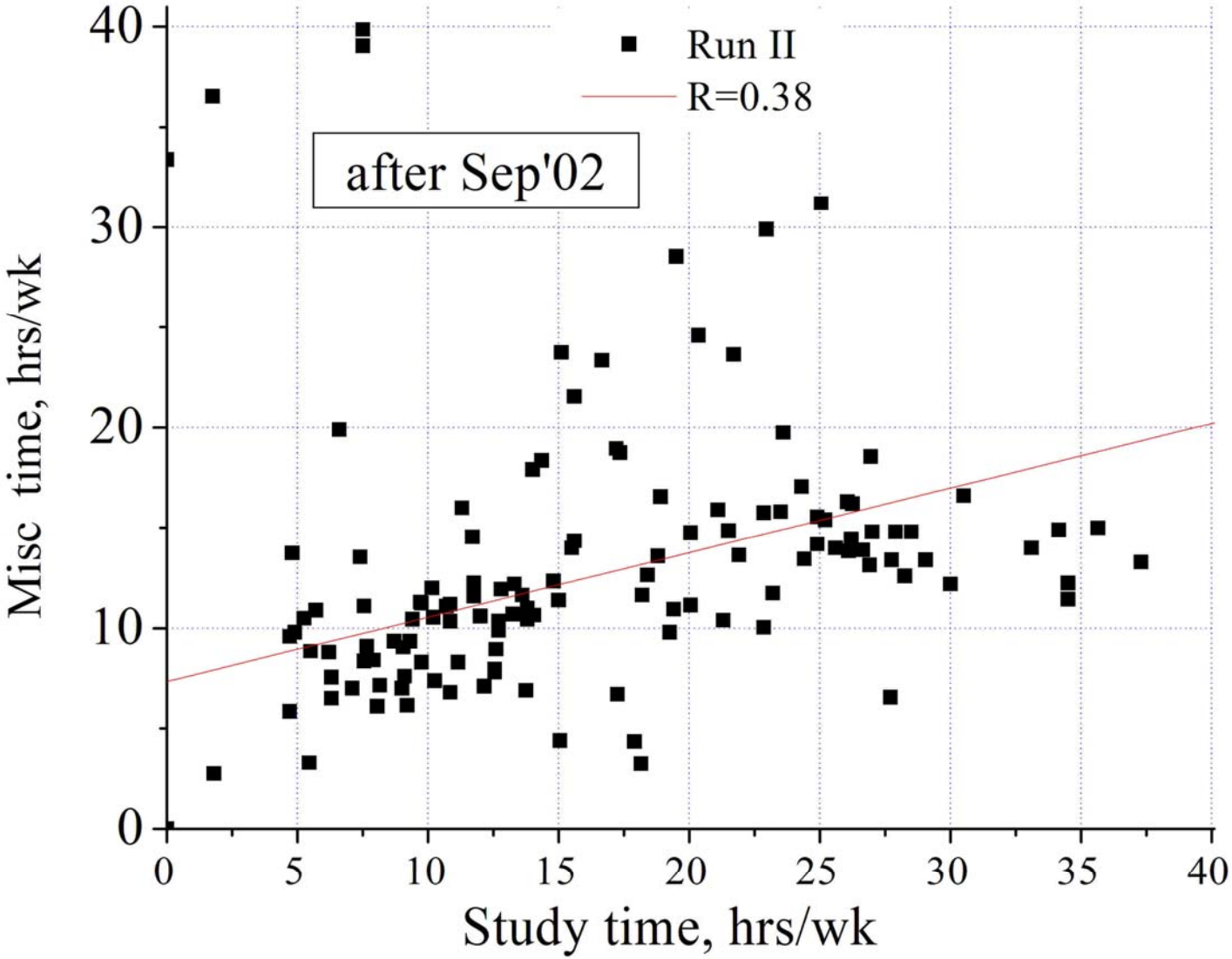
- Since July'04 , pabr stacking rate went up some 25% due to slip stacking – that should be seen in the integrated luminosity as well
- Having more pbars from RR – which have lower emittance - should help to improve overall transfer efficiency, at least, to reduce the losses 150 and on the ramp
  - Slide 59 below shows that pbar (and proton, by the way) losses on the ramp has been reduced since July 04
  - That may reduce the contribution I originally attributed to the octupoles (from 7% to some 3-5%
  - On the other hand, octupoles were implemented in the middle of the period when we routinely got pbars from RR and AA – and 150 GeV efficiencies improved (both p and pbars)
- Additional cooling in the AA during shot setup also led to smaller pbar emittances – is that seen?
- Slide 60 below shows non-luminous losses (beam-beam induced losses) now reduce luminosity lifetime by 12% - that is 8% improvement compared to July 2004. The gain mostly came from proton lifetime improvement – so, we should give proportional credit to a proton WP change when Tev moved it off $7^{th}$ and $12^{th}$ order resonances - ??

# BACK UP SLIDES

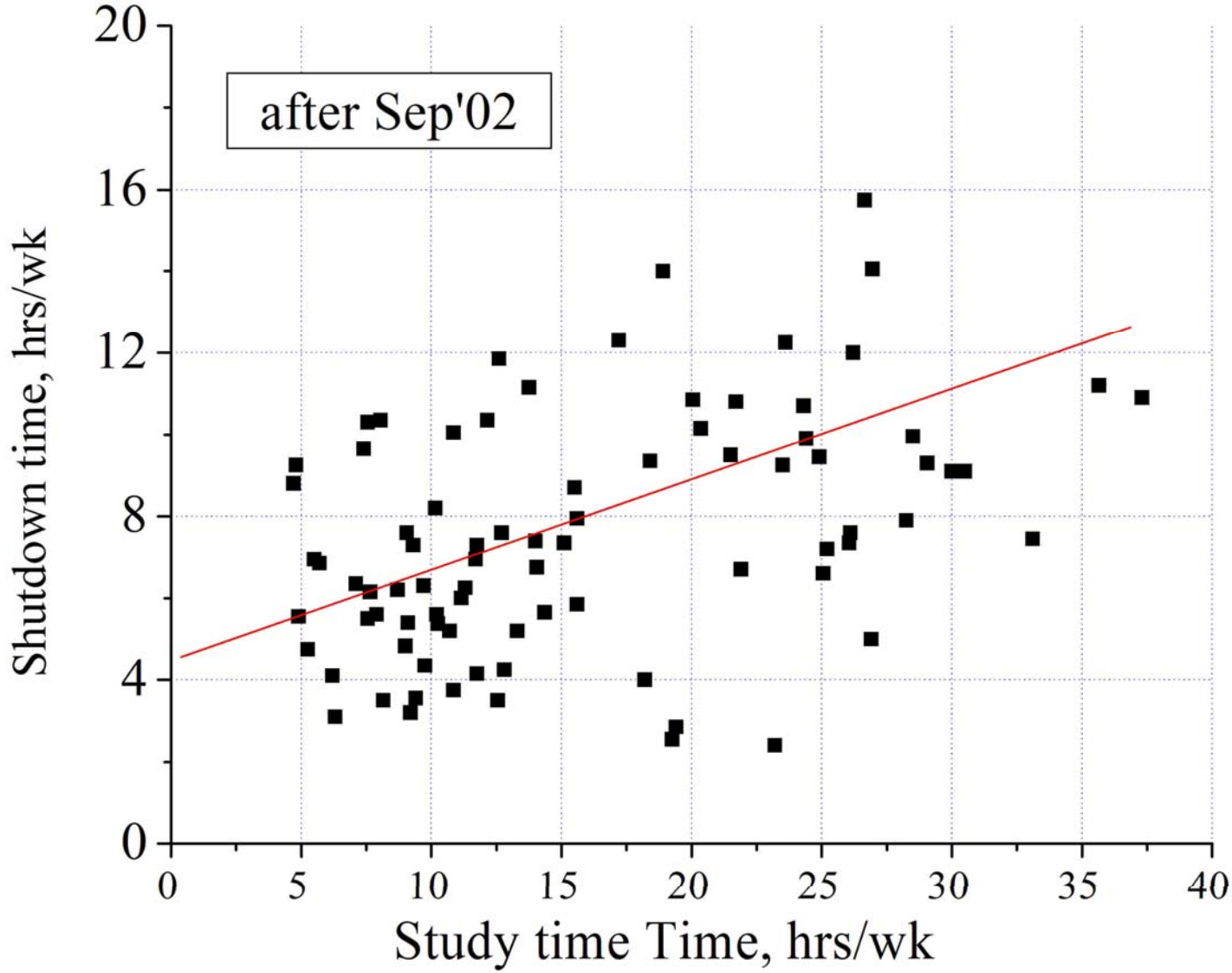
# Shot SetUp time /wk in Run II



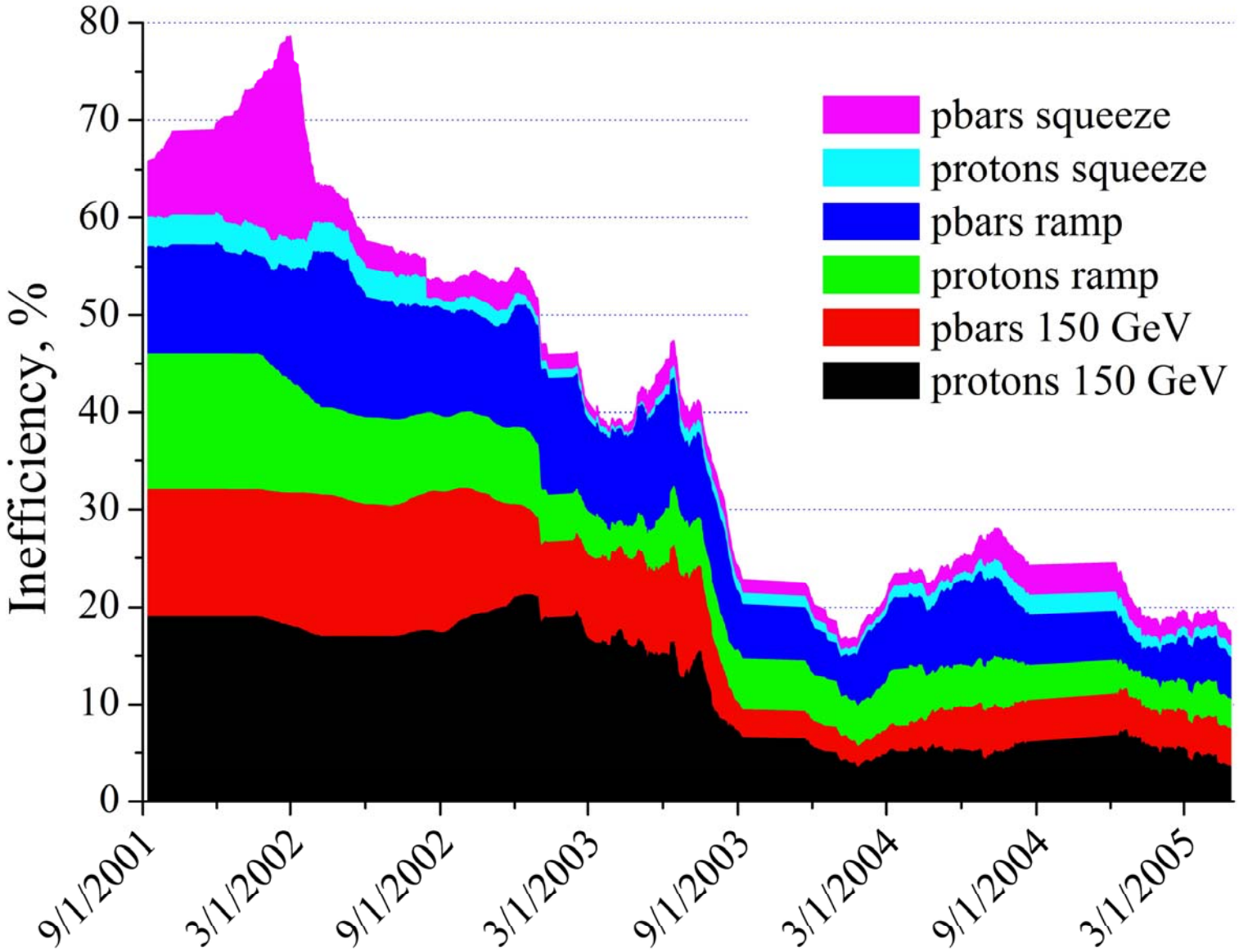
# "Misc" time vs "Study" time – correlation?



# Shot SetUp Time ~ Studies?



# Tevatron Inefficiencies: 2001-2005




???

Jun 2009

# L-Lifetime Affected by Beam-Beam